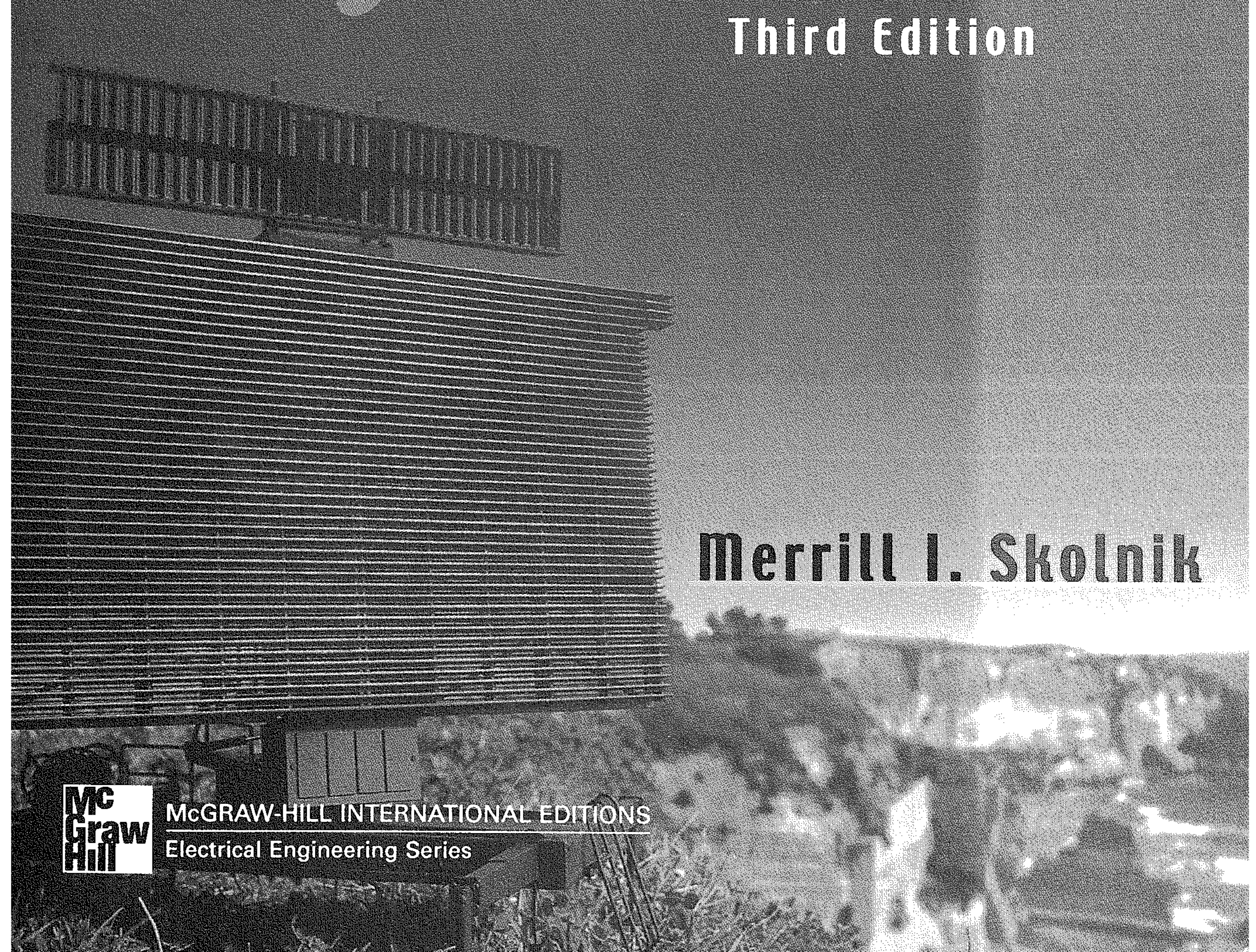
Introduction to RADAR systems

Third Edition



Merrill I. Skolnik

McGRAW-HILL INTERNATIONAL EDITIONS
Electrical Engineering Series

chapter

10

Radar Transmitters

10.1 INTRODUCTION

The radar systems engineer would like a transmitter to provide sufficient energy to detect a target, be easily modulated to faithfully produce the desired waveforms, generate a stable signal so that doppler signal processing can be performed without transmitter noise masking the doppler-shifted received signal, provide the needed signal bandwidth and tunable bandwidth, be of high efficiency, be of high reliability, be easy to maintain, have long life, be able to operate with a minimum of personnel, be of a size and weight suitable for the intended application, and be of affordable price. All of the above can be obtained, but seldom all together in one transmitter. Compromise is necessary.

Some radar transmitters have to generate large peak power as well as large average power; but it is the average power (which relates to energy) that is the measure of radar performance rather than peak power. It was seen in Chap. 2 that the range of a radar is proportional to the fourth root of the radar transmitter's average power. To increase the range of a radar by one order of magnitude (a factor of ten) the transmitter power has to be increased by ten thousand. Although there have been radars with average powers greater than a million watts, power cannot be increased without limit since high-power transmitters are heavy, take up space, and can consume much prime power (the power taken from the local power company) or fuel for motor-driven electrical generators.

An indicator of the performance of a radar is the product of the antenna area times the transmitter's average power. Tom Weil[1] described quite well the problem of choosing between high transmitter power and a large antenna as follows:

It obviously would not make sense for a radar to have a huge, costly antenna and a tiny, inexpensive transmitter, or vice versa, because doubling the tiny part would allow cutting the huge part in half, which would clearly reduce total system cost. Thus, minimizing total system cost requires a reasonable *balance* between the costs of these two subsystems. The result, for any nontrivial radar task, is that significant transmitter power is always demanded by the system designers.

Radar transmitters have been based on either a power amplifier, such as a klystron, or a power oscillator, such as a magnetron. In the early days of microwave radar in the 1940s and 1950s, the magnetron power oscillator was used almost exclusively since it was the only high-power microwave tube available at the time. It did an outstanding job in making microwave radar a reality in World War II, but it had many serious limitations. Magnetrons are noisy devices that limit the MTI improvement factor that can be obtained. Although they can produce high peak power (megawatts), they are not capable of large average power, and their signal output cannot be readily modulated to produce pulse-compression waveforms. All of these disadvantages are overcome with amplifiers such as the klystron, traveling wave tube, and the transistor. Modern high-performance radars almost always employ some sort of power amplifier as the transmitter. The magnetron appears to be limited to those applications where its relatively small size and lower cost are more important than its limitations.

Most of the discussion in this chapter is about the RF power source. A transmitter, however, is more than just the active RF power source. It includes the exciter and driver amplifiers that provide the signal to be amplified if the power source is an amplifier. If the transmitter generates a pulse waveform, a pulse modulator of some type is needed (except for RF power sources that are self-pulsed by the input waveform, as are transistors). There must be a d-c power supply for generating the necessary voltages and currents to operate the RF power device; means to remove the heat dissipated, including a heat exchanger when liquid cooling is used; protection devices for dissipating high-voltage arc discharges; safety interlocks; monitoring devices; isolators; high-voltage cable; insulating-oil tanks (to immerse high-voltage cathode bushings to prevent corona and high-voltage breakdown); and lead shielding of X-rays when high voltages are used. Not all high-power radar transmitters need all of the above, but an RF power source is useless without the ancillary devices required to make it function.

The efficiencies of RF power sources typically might range from about 10 percent to about 60 percent. This is the *RF conversion efficiency,* defined as the ratio of RF power output available from the device to the d-c power input to the electron stream. It is the efficiency of interest to the tube or RF power source designer, but it is not the best measure for the radar systems engineer. A better measure is the *transmitter system efficiency,* which is the ratio of the RF power available from the transmitter to the total power needed to operate the transmitter. The total power includes the power to generate the electrons at the cathode, the power to generate any electromagnetic fields required for containing the electron beam, the power to cool the device, and any other power needed for the proper operation of the transmitter. If, for example, the RF conversion efficiency were 40 to 50 percent, the transmitter system efficiency might be 20 to 25 percent, or less. Thus one usually doesn't want to start with a power source whose RF conversion efficiency is only 10 to 15 percent, unless the power is so low that efficiency is not an important consideration.

For maximum efficiency, most high-power RF power sources operate saturated, meaning they are either completely on or completely off, with no intermediate power levels. This is all right for a radar that generates a rectangular-like pulse waveform. There are times, however, when it might be desired to have an amplitude-tapered, or shaped, pulse (for example, to reduce the time sidelobes in pulse compression waveforms or to minimize the effects of RF interference to other users of the electromagnetic spectrum). Highly shaped transmission waveforms are seldom found in high-power microwave radar systems because of their lower efficiency. Transistor amplifiers can be operated in what is called class-A operation so that there is a linear relationship between the output and input signal amplitudes. The efficiency of a class-A amplifier, however, is much less than that which would be achieved with the same device operated class-C. (Class-C amplifiers are nonlinear and are self-pulsing in that they generate pulses when the RF drive is turned on and off.) Thus, a microwave radar transmitter is almost always operated in saturation and not as a linear device.

High reliability and long life are important for a transmitter. The life of most RF power sources can be many thousands or many tens of thousands of hours, as will be discussed when describing the individual devices later in this section. If a transmitter's mean time between failures (MTBF) is not as long as expected, factors other than the RF power source are often at fault. Likely candidates are fans and blowers, the wrong type of coolant, RF connectors and coolant fittings damaged, coolant lines clogged, and leads that are broken, mishandled, or abused. Conservative mechanical and electrical design and procurement practices that guarantee reliability from suppliers are needed for a trouble-free transmitter (or anything else). The user of RF power sources also needs to help in avoiding less than the achievable reliability. For example, A. S. Gilmour[2] states "If the truth were known, it could well be that over 50 percent of all failures are the fault of the users, rather than the tube manufacturers."

Summary of Radar RF Power Sources The different RF power sources available for high-power radar application include the klystron, traveling wave tube, solid-state transistor amplifier, Twystron, magnetron, crossed-field amplifier, amplitron, grid-controlled vacuum tube, extended interaction amplifier, gyrotron, and others. None provide all the desirable features that might be wanted. Some are no longer as popular as they once were. The choice depends in large part on the application and its constraints. Each of these devices will be briefly summarized below and described in more detail later in the chapter. All except the magnetron are power amplifiers. The gyrotron can be either an amplifier or an oscillator.

Klystron This is an excellent radar tube when it can be employed. It has high gain and good efficiency, and is capable of higher average and peak power than most other RF power sources. It can have wide bandwidth (in the vicinity of 8 to 10 percent relative bandwidth*) when its power is large, long life (tens of thousands of hours), low interpulse noise, and good stability for doppler processing. When large peak powers are generated it requires very high voltage and X-ray shielding.

*Relative, or fractional, bandwidth in percent = $(\Delta f/f_0) \times 100$, where Δf = absolute bandwidth and f_0 = center frequency.

Traveling Wave Tube (TWT) TWTs have slightly less power, slightly less gain, and slightly less efficiency than a klystron; but they are capable of wide bandwidth, especially at modest power levels. At high power levels the TWT bandwidth is lower than what can be achieved at lower powers, but it is still relatively large.

Hybrid Klystrons These are similar to klystrons, but with one or more of the resonant cavities replaced by multiple cavities similar to what are used in a TWT. There are at least three versions: the *Twystron,* the *extended interaction klystron,* and the *clustered cavity klystron.* Bandwidths can be 15 to 20 percent, or more. Extended interaction klystrons have also been used for modest power millimeter-wave transmitters.

Solid-State Transistor Amplifiers These are capable of wider bandwidth than most other RF power sources. They operate with low voltages, ease of maintenance, and have promise of long life. They are inherently of low power so that a large number of individual devices must be combined to generate sufficient power for most radar applications. For adequate efficiency, they should be operated at high duty cycles, which require that they generate long pulses and employ pulse compression.

Magnetron The magnetron is generally smaller in size and utilizes lower voltage than the klystron; but its average power is limited and it has poor noise and stability characteristics, which restrict its ability to cancel clutter when used in an MTI radar.

Crossed-Field Amplifiers These are capable of high power, good efficiency, and wide bandwidth, but are of relatively low gain (about 10 dB). Lower voltage, just as with the magnetron, means that X-rays are not usually a problem. Crossed-field amplifiers are generally noisier and less stable than most other RF power sources.

Grid-Control Tubes These are modern versions of the classical triode and tetrode vacuum tubes originally introduced early in the twentieth century. They are a good power source for UHF radars, but they have been largely replaced by solid-state devices.

Microwave Power Module This is a combination of a modest power TWT driven by a solid-state device that competes favorably with high-power solid-state modules in some applications.

Gyrotrons These can produce very high power in the millimeter wave region, but they require large magnetic fields. They have had only modest application in operational radar systems.

RF power sources may be grouped into four general classes: (1) linear-beam tubes, (2) solid state, (3) crossed-field tubes, and (4) others not included in the first three. The klystron, traveling wave tube, magnetron, and crossed-field amplifier are *slow-wave devices* in that the phase velocity of the electromagnetic wave in the RF structure is slowed so as to be approximately equal to the velocity of the electron stream in order for (d-c) energy from the electron beam to transfer to electromagnetic energy in the (RF) signal.[3] The gyrotron, on the other hand, is a *fast-wave device* in that the phase velocity of the electromagnetic wave exceeds the speed of light in the interaction region.

10.2 LINEAR-BEAM POWER TUBES

In the linear-beam tube the electrons emitted from the cathode are formed into a long cylindrical beam that receives the full potential energy of the electric field before the beam enters the RF interaction region. The klystron, traveling wave tube, Twystron, and extended interaction amplifier are examples of linear-beam tubes. The last two are basically hybrid devices that combine the technology of the klystron with the RF structure of the TWT. An axial magnetic field is used in linear-beam tubes to confine the electron beam and keep electrons from hitting the RF structure. Transit-time effects, which can limit conventional vacuum tube performance at high frequencies, are used to good advantage in linear-beam tubes to *density modulate* the uniform d-c electron beam to create bunches of electrons from which RF energy can be extracted.

Linear-beam tubes can produce much higher power than other power sources. Klystrons are capable of more than a megawatt of average power. High power is a result, in part, of their larger size and high voltages. Thomson-CSF in France produced a UHF klystron that delivered more than one MW CW power. It was 5 m (16.4 ft) long and weighed 1400 kg (3000 pounds).[4] On the other hand, *X*-band klystron and TWT transmitters producing many kilowatts of average power can be made light enough and small enough to fly in the nose of military fighter/attack aircraft.

Klystron A sketch of the principal parts of a klystron is shown in Fig. 10.1. At the left is the cathode which emits a stream of electrons that is formed into a narrow cylindrical beam by the *electron gun*. The electron gun consists of the cathode that is the source of electrons, a modulating anode or other beam-control electrode to provide a means for turning the beam on and off to generate pulses, and the anode. The electron emission density at the surface of the cathode is less than that required for the electron beam, so a large-area cathode surface is used and the emitted electrons are caused to converge to a narrow beam of high electron density. The multiple RF cavities, which correspond to the *LC* resonant circuits of conventional lower-frequency amplifiers, are at anode potential. Electrons are not intentionally collected by the anode, as in some other tubes; instead they are

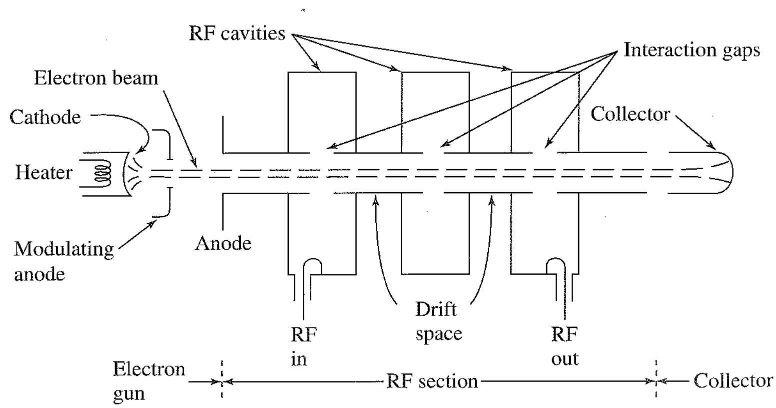


Figure 10.1 Representation of the principal parts of a three-cavity klystron amplifier.

removed by the collector electrode (shown on the right) after the beam has given up its RF energy to the output RF cavity.

The RF input signal is applied across the *interaction gap* of the first cavity. Those electrons which arrive at the gap when the input signal voltage is a maximum (peak of the sinewave) experience a voltage greater than those electrons which arrive at the gap when the input is at a minimum (trough of the sinewave). Thus the electrons that see the peak of the sinewave are speeded up and those that see the trough are slowed down. The process whereby some electrons are speeded up and others slowed down is called *velocity modulation* of the electron beam. In the *drift space,* electrons that are speeded up during the peak of one cycle catch up with those slowed down during the previous cycle. The result is that the electrons of the velocity-modulated beam become "bunched," or density modulated, after traveling through the drift space. A klystron usually has one or more appropriately placed intermediate cavities to enhance the bunching of the electron beam, which increases the gain. If the interaction gap of the output cavity is placed at the point of maximum bunching, power can be extracted from the density-modulated beam. The gain of a klystron might be 15 to 20 dB per stage when synchronously tuned (all cavities tuned to the same frequency), so that a four-cavity (three stage) klystron might provide over 50 dB gain.

After the bunched electron beam delivers its RF power to the output cavity, the energy of the electron beam that remains is dissipated when the spent electrons are removed by the collector. The energy dissipated by the collector is energy lost and reduces the efficiency of the tube. If the collector is insulated from the body of the tube and a negative voltage is applied to the collector, the electrons in the spent beam will have lower kinetic energy so that less heat is produced when they impact upon the collector.[5] This results in an increase in the efficiency of the tube. There is a spread, however, in the velocities of the electrons in the beam; so if the potential is too negative, some of the slower velocity electrons will be returned to the walls of the RF section of the tube and be collected as body current, with a decrease in efficiency. This problem is overcome by employing a collector with several segments insulated from one another and with different negative potentials so that electrons with different velocities can be separated and collected at their optimum potential. Figure 10.1 shows a single-stage collector, but both the klystron and TWT usually employ multiple-stage depressed collectors for greater efficiency. The multiple stages (three or four might be typical in a radar tube) are at intermediate voltages, which allow catching the spent electrons at a voltage near optimum.

According to Weil,[1] a klystron with a peak power of 1 MW requires a voltage of about 90 kV. Gains might vary from 30 to 70 dB, bandwidths from 1 to 8 percent, and efficiencies from 40 to 60 percent (with depressed collectors).

A long solenoid (not shown in Fig. 10.1) with iron shielding around its outside diameter surrounds the high-power klystron to provide an axial magnetic field that confines the electrons to a relatively long, thin beam and prevents the beam from dispersing. Cooling might have to be provided for the electromagnets. In a high-power klystron, from 2 to 5 percent of the beam power might normally be intercepted by the interaction structure, or body of the tube. If the beam were not properly confined by the external magnetic field, the stray electrons impinging on the structure of the tube could cause it to overheat and possibly be destroyed. Protective circuitry is normally employed to remove

the electron beam voltage in the event the magnetic field fails to keep the beam properly focused.

The electron beams of klystrons and TWTs also can be confined with permanent magnets. They do not require power or cooling, and the various protective circuits needed with solenoids are eliminated. Permanent magnets have been used with high power tubes, but they are quite heavy.[6,7] A significant reduction in weight, however, can be obtained with a periodic permanent-magnet (PPM) focusing system that consists of a series of magnetic lenses. These lenses employ washer-shaped disk magnets separated by iron pole pieces. The PPM replaces the uniform field of a solenoid with a periodic, essentially sinusoidal, field having the same rms value as the uniform field. Samarium cobalt is an example of a magnet material that has been widely used for tubes requiring permanent magnets. In the past, PPM focusing was usually not suited for large average-power tubes, but it has been successfully applied to high peak-power klystrons, as described next.

High-power klystrons have been used ever since the 1950s for linear accelerators to generate energetic beams of charged particles for research on the physics of high-energy particles. Many advances in klystron capability have been obtained from the development of klystrons for this purpose. These advances have, of course, been of benefit to radar as well. Although the invention of the klystron amplifier was reported in 1939, before the invention of the magnetron, it was not used or further developed significantly during World War II. It did not find its way into radar application until the development of a 20-MW peak power klystron, used in one of the first linear accelerators, was reported in 1953 by Stanford University. Thus the high-power klystron, which is a very important power source for radar, was a by-product of basic research in science. Work continued at the Stanford Linear Accelerator Center (SLAC) to develop high peak-power klystrons for electron-positron colliders. The klystron for the Next Linear Collider (NLC)[8] is at a frequency of 11.424 GHz, with a peak power of 60 to 75 MW using periodic permanent magnets made of neodymium-iron boron. The PPM with 10 pounds of permanent magnets replaces a 1/2-ton, 10-kW focusing solenoid. The NLC uses 6528 klystrons, which means that a total of 65 MW of solenoid power is avoided. The use of PPM, as well as having a tube with 60 percent efficiency, reduces "the NLC electric power bill by tens of millions of dollars per year." The tube requires an electron beam voltage of 490 kV. The average life of the *S*-band klystrons used for the previous Stanford Linear Collider (SLC) was 50,000 hours, and it is expected that a similar life will be obtained with the *X*-band NLC klystron. The manufacturing cost was said to be $30,000 per tube. If the tube delivers 75 MW with a pulse width of 1.5 μs and a prf of 120 Hz, its average power is 13.5 kW.

Bandwidth of a Klystron The frequency of a klystron is determined by its resonant cavities. When all the cavities are tuned to the same frequency, the gain of the tube is high but the bandwidth is narrow, usually a fraction of one percent for a tube of modest power output. This is called *synchronous tuning.* To maximize the klystron's efficiency the next to last (penultimate) cavity is tuned upward in frequency and is outside the passband. Although the gain is reduced by about 10 dB, the improved electron bunching results in greater efficiency and in 15 to 25 percent more output power.[9] Broadbanding of a multicavity klystron may be accomplished by *stagger tuning* the cavities, similar to the method for broadbanding a conventional multistage IF amplifier. Stagger tuning a klystron is not

precisely analogous to stagger tuning an IF amplifier because of interactions among the cavities that can cause the tuning of one cavity to affect the tuning of the others. The VA-87 four-cavity S-band synchronously tuned klystron amplifier with a 20 MHz bandwidth and a 61 dB gain can have a 27 MHz bandwidth and a 57.6 dB gain when tuned for maximum power.[10] When stagger tuned it has a 77-MHz bandwidth (2.8 percent) and a gain of 44 dB.

Theory shows that the bandwidth of a klystron can be significantly increased by increasing its power and its beam perveance (which is defined as the beam current I divided by beam voltage V to the 3/2 power, or $p = I/V^{3/2}$). A 10 MW peak power klystron, for example, can have an 8 percent bandwidth, as compared to a 200 kW tube which might have a 2 percent bandwidth, and a 1 kW tube having only a 0.5 percent bandwidth.[10] High-power multicavity klystrons can be designed with bandwidths as large as 10 to 12 percent.

Frequency Changing, or Tuning[6,9] Conventional narrowband klystrons may have their frequency changed mechanically over a relatively wide frequency range. The individual cavities of a klystron can be changed in frequency (or tuned) by having a flexible wall in the resonant cavity (tuning range of about 2 or 3 percent), by a movable capacity element in the cavity (10 to 20 percent tuning range) or by a sliding contact movable cavity wall.

It can be tedious to tune a multiple-cavity klystron because of the interactions among the several cavities. Conventional gang-tuning is complicated since the resonant cavities do not have the same tuning rates. The *channel tuner mechanism*[6] avoids the problem of frequency tracking of the resonant cavities by pretuning the cavities, generally at the factory. The tuning information is stored mechanically within the tuner mechanism. When a particular frequency is selected, the tuner mechanism provides the correct tuner position for each cavity to furnish the desired klystron frequency response. The channel tuner mechanism is in a box attached to the klystron with gears to simultaneously set the tuning plungers at each cavity to their predetermined positions for a given frequency. The tuning plungers can be actuated manually or remotely by push buttons and a servomotor. The frequency can be changed in seconds.

Power Some of the highest power radar transmitters have used klystrons. The ability of a klystron to produce higher power than other microwave power sources is, in part, due to its geometry. The regions of beam formation, RF interaction, and beam collection are separate. Each can be designed to best perform its own particular function independently of the others. The cathode, for example, is outside the RF field and need not be restricted to sizes that are small compared to a wavelength. Large cathode area and large interelectrode spacings may be used to keep the emission current densities and voltage gradients to reasonable values. The only function of the collector is to dissipate heat. It can be a shape and size best suited for satisfying the average or peak power requirements without regard for conducting RF currents, since none are present.

Efficiency It is said in Ref. 8 that Robert Symons found that the best values of efficiency reported for klystrons worldwide followed the relation

$$\text{RF efficiency (percent)} = 90 - 20 \times \text{microperveance} \quad [10.1]$$

where the microperveance is the perveance $I/V^{3/2}$ times 10^6, where I = beam current and V = beam voltage. Thus the lower the microperveance (or perveance) the higher will be the klystron efficiency. The perveance affects other properties of the klystron, including its bandwidth and power. Higher efficiency often requires, therefore, a reduction in bandwidth and lower power.

Reliability and Life High-power transmitters employing power vacuum tubes have sometimes had the unwarranted reputation for poor reliability and short life. There is much evidence to the contrary for the klystron tube. Gilmour[11] reports the mean time between failures (MTBF) of eleven different applications of klystrons in radar systems (not identified by type or power). The MTBF for these examples varied from 75,000 hours to 5000 hours, with an average value of about 37,000 hours for all eleven applications. (There are 8760 hours in a year.) The VA-842 high-power klystron tube used by the U.S. Air Force in the original Ballistic Missile Early Warning System (BMEWS) had a demonstrated life in excess of 50,000 hours. Symons[12] reports that one of the BMEWS tubes he designed in 1958 was still operating after 240,000 hours when the radar in Greenland was replaced by the solid-state Pave Paws radar.

An S-Band Klystron The venerable VA-87 klystron built by Varian (now Communications & Power Industries) was widely used in the FAA's S-band Air Surveillance Radars commonly found at major airports. It was a six-cavity tube tunable from 2.7 to 2.9 GHz, the frequency band reserved for air-traffic control radars. It had a peak power of from 0.5 to 2 MW, average power of from 0.5 to 3.5 kW, 50 dB gain, 45 percent efficiency, and a one-dB bandwidth of 39 MHz. It demonstrated a mean-time-between-failure (MTBF) rate of 72,000 hours. A similar tube was used in the Nexrad Doppler Weather Radar, but with bandwidth from 2.7 to 3.0 GHz.

Traveling Wave Tubes (TWT) Like the klystron, the traveling wave tube is also a linear-beam tube with the cathode, RF circuit, and collector separated from one another. The klystron and the TWT were invented at different times in different parts of the world, but they are similar to one another. There is continuous interaction of the electron beam and the RF field over the entire length of the propagating structure of the traveling wave tube. In the klystron, on the other hand, the interaction occurs only at the gaps of a relatively few resonant cavities. The chief characteristic of a TWT is that it has wide bandwidth. Low power TWTs with a helix slow-wave RF structure are capable of octave bandwidths. With the high peak powers required of most radar applications, the bandwidths available with high-power TWTs are, however, much less than an octave.

The major parts of a TWT are indicated in Fig. 10.2. A helix is shown for the slow-wave RF structure even though the helix is seldom used in TWTs found in radar applications. The electron beam is similar to that of the klystron. Both the TWT and the klystron employ the principle of velocity modulation to cause the electron-beam current to be periodically bunched (density modulation). The electron beam passes thorough the RF interaction circuit known as the *slow-wave structure,* or periodic delay line. The velocity of propagation of the RF signal is slowed down by the periodic delay line so that it is nearly equal to the velocity of the electron beam. This is the reason that the helix and

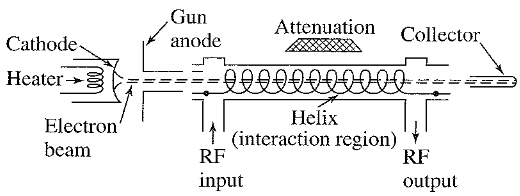


Figure 10.2 Representation of the principal parts of a traveling-wave tube.

other microwave circuits used in TWTs are called slow-wave structures. The synchronism between the electromagnetic wave propagating along the slow-wave structure and the d-c electron beam propagating inside the helix results in a cumulative interaction which transfers d-c energy from the electron beam to increase the energy of the RF wave, causing the wave to be amplified. Just as in the klystron, an axial magnetic field keeps the electron beam from dispersing as it travels down the tube.

After delivering their d-c energy to the RF field on the slow-wave structure, the electrons are removed by the collector, which is usually a multistage depressed collector, as was described for the klystron. It is easier to design a depressed collector for a TWT than for a klystron since the spent electron beam of a TWT might have a 20 percent spread in velocity, but the klystron might have a velocity spread of almost 100 percent.[5] Because the efficiency of a conventional TWT is usually lower than that of a klystron, the increase in efficiency in the TWT provided by the depressed collector has a greater relative effect than with a klystron.

Although a helix is shown in Fig. 10.2 as the slow-wave structure, it is seldom found in TWTs used for radar. The helix TWT is limited to voltages of about 10 kV and a peak power output of a few kilowatts,[1] which is generally too low for most radar applications. Other types of RF slow-wave structures have to be employed instead, and these do not have as wide a bandwidth as the helix. A modification of the helix known as the ring-bar circuit can be used if the peak power is less than about 100 to 200 kW. One example is the Raytheon QKW-1671A, a tube suitable for air-surveillance radars. It has a peak power of 160 kW, duty cycle of 0.036, 70-μs pulse width, 45-dB gain, and a 100-MHz bandwidth. The Air Force Cobra Dane phased array radar uses 96 QKW-1723 ring-bar TWTs, each with a peak power of 175 kW and average power of 10.5 kW. The Cobra Dane operates from 1175 to 1375 MHz.

Powers greater than 200 kW are obtained with the coupled-cavity circuit, of which the so-called "cloverleaf" is an example. The bandwidth, however, is less than that of lower power TWTs. The individual unit cells of the coupled-cavity circuit resemble klystron resonant cavities. Several tens of these klystron-like cavities are used for the slow-wave structure of a high-power TWT.[13] There is no direct coupling between the cavities of a klystron, but in the traveling wave tube, coupling is provided by a long slot in the wall of each cavity. There are two slots in each cavity (input and output) that are 180° apart in rotational position so they act similar to a folded waveguide.

An example of a TWT using a cloverleaf coupled-cavity slow-wave structure is the *S*-band VA-125A. It is liquid cooled and is capable of 3 MW peak power over a 300-MHz bandwidth, 0.002 duty cycle, 2-μs pulse width, and a gain of 33 dB. It was originally designed to be used interchangeably with the VA-87 klystron, except that the VA-125 TWT has a wider bandwidth and requires a larger power input signal because of its lower gain.

The bandwidth of a coupled-cavity TWT can be from 10 to 15 percent. When the power of a TWT is increased, its wide bandwidth decreases. On the other hand, when the power of a klystron is increased, its narrow bandwidth widens. As the power of these two tubes increase, their bandwidths become comparable. With high power, the klystron tends to be the preferred tube since it doesn't experience the stability problems of the TWT.

Although the TWT and the klystron are similar in many respects, a major difference is that there is feedback along the slow-wave structure of the TWT, but the back coupling of the RF energy in the klystron is negligible. If there is a mismatch at the input of the TWT and if sufficient energy is fed back to the input, undesired oscillations can result. To reduce the amount of feedback energy to an insignificant level, attenuation has to be inserted in the slow-wave structure. The attenuation may be distributed or lumped, but it is usually found within the middle third of the tube. The loss introduced to attenuate the feedback also reduces the power of the forward-traveling wave, and is therefore undesirable. The loss in the forward wave can be avoided by the use of *severs,* which are short internal terminations designed to dissipate the reverse-directed power without seriously affecting the power in the forward direction. The number of severs depends on the gain of the tube; one sever is used for each 15 to 30 dB of tube gain.[1]

The efficiency of TWTs is less than that of the klystron because of the necessity for including attenuation or severs. Efficiency is also reduced by the presence of relatively high RF power over an appreciable fraction of the entire structure.

In some traveling-wave tubes with coupled-cavity circuits, oscillations appear for an instant during the turn-on and turn-off portions of the pulse.[1] These are called *rabbit-ear oscillations* because of their characteristic appearance when the RF envelope of the pulse waveform is displayed visually on a CRT. They are undesirable in some military applications since they might provide a distinctive feature for recognizing a particular radar. Weil[1] describes some of the ways rabbit-ear oscillations can be avoided.

TWT MTBF The mean time between failures (MTBF) is given by Gilmour[11] for nine different types of coupled-cavity TWTs. (The type of TWT, frequency, and power are not mentioned.) The MTBFs of these nine classes vary from a high of 17,800 hours to 2200 hours, with an average of 7000 hours for all nine classes of tubes. TWTs for space applications, which are of lower power than radar tubes, are said by Gilmour to have MTBFs of the order of one million hours.

Hybrid Variants of the Klystron By judiciously combining the best features of the klystron and the traveling wave tube, an RF power source can be obtained which has bandwidth, efficiency, and gain flatness better than either the conventional klystron or TWT. This is achieved by replacing one or more of the klystron resonant cavities with broader bandwidth cavities that are more like the coupled-cavity circuits used in traveling wave tubes. There have been three variants of the klystron in which this is done: the *Twystron,* the *extended interaction klystron,* and the *clustered-cavity klystron*. Such combinations of klystrons and TWTs are sometimes called *hybrid tubes*.[14]

Twystron The bandwidth of a klystron is limited by the output resonant cavity. It cannot be made broadband without a decrease in efficiency. Since coupled-cavity slow-wave

circuits have broader bandwidth than klystron resonant cavities, replacing the output cavity of a klystron with a TWT coupled-cavity circuit can significantly increase the bandwidth as well as achieve a slight increase in efficiency. Although the output is a TWT slow-wave circuit, the driver portion of the tube (the intermediate cavities and the input cavity) consists of resonant cavities that are stagger tuned. Such a tube is called a Twystron, a trademark name of Varian (now Communications & Power Industries, or CPI). The VA-145 Twystron has demonstrated a 14 percent 3-dB bandwidth (12 percent 1-dB bandwidth), 48 percent efficiency, and 41 dB gain at midband.[1]

Extended Interaction Klystron (EIK) In this device, the single-gap resonant cavity of a klystron is replaced by a resonated slow-wave TWT-like circuit. The use of slow-wave coupled resonators can be applied to the prior cavities as well as the output cavity. The extended interaction amplifier (EIA) klystron can have a high average power; for example, 1 MW CW at X band using a five-cavity resonator.[15] It has broader bandwidth than a klystron, but less than that of a TWT. EIKs also have been used for low-power millimeter wave tubes. A 150-W average power 95-GHz klystron, advertised by CPI Canada, is claimed to have a 1.5-kW peak power, 500-MHz bandwidth, 25 percent efficiency, 45-dB gain, and to weigh 4.5 kg. There is also an extended interaction oscillator, or EIO, which has been used at millimeter wavelengths.

Clustered-Cavity Klystron The technique of grouping cavities was extended in what has been called a *clustered-cavity klystron* (CCK). In this tube, Fig. 10.3, the individual intermediate cavities of a multicavity klystron are replaced by pairs or triplets of artificially loaded low-Q cavities with Qs of one half or one third that of the single cavity they replace.[16] Similar groups of cavities are used in both the EIA and the CCK, but there is

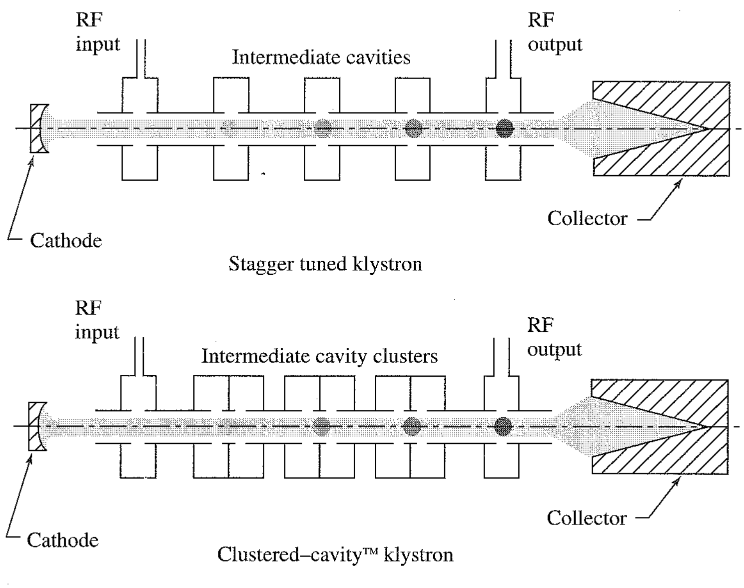


Figure 10.3 Comparison of a conventional staggered-tuned klystron (top) and a clustered-cavity klystron (bottom). The shaded circular regions represent bunching of the electrons. (From Symons and Vaughan,[16] Copyright 1994 IEEE.)

no inductive or other coupling between cavities in the CCK as there is in the EIA. Theory indicates that bandwidths of 30 percent should be obtained in megawatt klystrons using fifteen intermediate cavities in triplets. In practice, 20 percent bandwidths have been observed. This form of structure also provides the greatest bandwidth in the shortest length. Clustered-cavity klystrons might be more complex and costly than a klystron, but they are less complex and of less cost than a comparable TWT or Twystron.[1] Symons,[12] the inventor of the clustered-cavity klystron, states that two of these tubes can be used instead of the two narrower-band klystrons in the AWACS radars. Redundant operation is provided, without a large weight penalty, since either of the clustered-cavity klystrons provide full operational capability similar to the redundancy commonly employed in FAA radars.

10.3 SOLID-STATE RF POWER SOURCES

Use of Solid-State Amplifiers for Radar Transmitters The solid-state RF power generation device usually of interest for radar application has been the transistor amplifier, both silicon bipolar and gallium arsenide FET. An individual transistor amplifier device is inherently of low power and low gain, but it operates with low voltages and has high reliability.

A single microwave transistor might have an average power capability from a few watts to over a hundred watts, depending on the frequency and the duty cycle. The lower the frequency the greater can be the power. To increase the power, transistors may be operated in parallel, and with more than one stage to increase the gain. A single power *module* might, for example, consist of eight transistors, with four operating in parallel as the final stage, two in parallel as the next to last stage, and two in series as the driver stages. To achieve the high powers required for most radar applications, the outputs of many solid-state devices have to be combined in some manner. Combining of many devices can be achieved with microwave circuitry or by combining in space (radiating from many individual antenna elements of an array antenna).

Solid-state power devices of a given average power cannot be operated at high peak powers as can vacuum tubes. According to Borkowski,[17] "a microwave transistor capable of perhaps 50-W average power cannot handle much more than 100 to 200 W of peak power without overheating during the pulse." For this reason solid-state amplifiers for radar generally operate in the vicinity of 0.1 duty factor, instead of the 0.001 to 0.01 duty factors common with high-power vacuum tube RF power sources. Thus when solid-state devices are employed in radar transmitters they have long pulse widths and require pulse compression to obtain useful range resolution. Long pulses are not always desired by the radar engineer, but they have been accepted as one of the prices to be paid for the use of solid state.

There are at least four ways that solid-state devices can be employed in radar: (1) as a transmitter for a low-power application, (2) as a high-power transmitter where a large number of individual transistors are combined with microwave circuitry, (3) with many modules distributed on a mechanically steered planar array (such as a 3D radar), and (4) with a module at each of the many elements of an electronically scanned phased array

(also called an active aperture). In the last two, the power from the many solid-state transmitter modules is "combined in space."

Low-Power Transmitter The solid-state device is used as a direct replacement for a vacuum tube when the radar waveform is of low power and of high duty cycle or CW. Examples are the FM-CW radar altimeter, doppler (police) speedmeter, and the airborne doppler navigator. The solid-state transmitter has been highly successful in such applications. It has been difficult, however, for solid-state to replace the small magnetron in the civil marine radars found on many ships and pleasure boats because this radar market is highly competitive and low price is important for success. The same appears to be true for the absence of solid-state transmitters for the nonradar application of microwave ovens for the household market.

High-Power Transmitter The solid-state transmitter has replaced the high-power vacuum tube in some air-surveillance radars. A large number of transistors are combined to produce a single output that feeds a conventional antenna. (This was at one time called a "solid-state bottle," but such transmitters are housed in cabinets which do not resemble "bottles.") Two such transmitters will be described.

One of the first solid-state radars to have its tube transmitter replaced by solid state was the AN/SPS-40, a modest UHF 2D shipboard air-surveillance radar used mainly by United States ASW (antisubmarine warfare) destroyers to provide conventional air-surveillance for keeping track of ASW aircraft.[18] It was developed by Westinghouse, Baltimore (now known as Northrop Grumman). This was a good example of a direct replacement since the tube transmitter operated with a long pulse (60 μs), pulse compression, and a moderate duty cycle (0.018), so that the solid-state transmitter could utilize the same waveform as did the original radar system. The basic transistor building block operated from 400 to 450 MHz, with 400- to 500-W peak power, 8-dB gain, and 55 percent efficiency. A module consisted of two stages with a total of 10 silicon bipolar transistors that produced 2500-W peak power out when the input was 120 W. There were 112 of these modules combined in two groups of 56 each to produce 250-kW peak power and 4 kW of average power. Each of the two groups of 56 modules was housed in its own cabinet. There was a third cabinet with the driver, power supplies, and some other devices. The transmitter was designed so that no damage occurred when a full short circuit was applied across the load. Both liquid and forced air cooling were used; and if the liquid cooling was lost, the transmitter could operate with 80 percent power (200-kW peak) with only air cooling. The loss of one module reduced the transmitter power output by 0.08 dB. The transmitter had good reliability due in part to its built-in spare modules. The solid-state transmitter for this radar cost more and was larger than the vacuum tube transmitter it replaced; but it was considered a success.

The Ramp (Radar Modernization Project) radar system was an L-band (1250 to 1350 MHz) air-traffic control Primary Surveillance Radar (PSR) located at major airports across Canada.[19] It was developed by Raytheon Canada and had a range of 80 nmi and an altitude coverage of 23,000 ft against a 2 m^2 aircraft target with 80 percent probability of detection. It used a solid-state transmitter with a peak power of 28 kW and an average power of 1.2 kW, which corresponded to a duty cycle of 0.068.

There were a total of 14 modules used in the RAMP PSR. Each module consisted of 42 identical class-C 100-W peak-power silicon bipolar transistors arranged in a 2-8-32 configuration to produce 2350 W of peak power. As described by Merrill,[20] "The transistors were arranged in a one-driving-four 'unit amplifier' format, with eight unit amplifiers in parallel so that 10 transistors were drivers while 32 were output devices." The 50-pound air-cooled module had a measured efficiency greater than 25 percent and a power gain greater than 16 dB.[17]

The 14 modules were combined as pairs to form seven transmitting channels. Only six of the seven channels were needed to meet the system requirement for a minimum peak power of 21 kW. The extra seventh channel permitted maintenance and repair to be performed on a failed channel while the remaining six channels were continuously available. The extra channel, therefore, allowed the radar to maintain a high availability. [The theoretical power output when N out of 7 channels are operating is $P_{out} = P_7\,(N/7)^2$, where P_7 = the power delivered by all seven channels.] The antenna for this radar was a 33 ft wide by 22 ft high reflector with 33.5-dB gain. It rotated at 12 rpm.

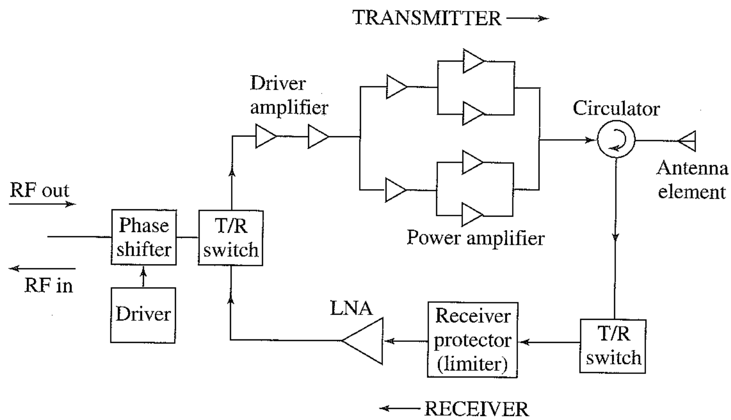
Modules Arranged on a Mechanically Scanned Planar Array, AN/TPS-59 Individual transmitter modules can be arranged on a mechanically scanning array antenna by placing one module at each element, but it has been more usual in such a radar to employ one module at each row of the antenna. This is the arrangement in the AN/TPS-59,[17] a transportable *L*-band 3D air-surveillance radar developed by GE, Syracuse, N.Y. (now Lockheed Martin) for the U.S. Marine Corps for air defense and ground-control of intercept (GCI). It was designed to detect a 1-m^2 fluctuating target within a 200-nmi range with 90 percent probability of detection, but it was also required to cover a volume out to 300 nmi in range and an altitude up to 100,000 ft. The rotating planar array antenna is 30 ft high by 15 ft wide and consisted of 54 rows, each with 24 dipole elements. The radar can operate within 1200 to 1400 MHz with 54-kW peak power and 9.7-kW average power, which results in the relatively high duty cycle of 0.18. A single pencil beam is electronically scanned over an elevation angle of 20° as the antenna rotates 360° in azimuth.

At each row is a transceiver, which is a miniature radar containing transmitter, receiver preamplifier, duplexer, phase shifter for steering in elevation, logic control, cooling, and power supply. Each transmitter module has ten 100-W amplifier units consisting of two 55-W silicon bipolar transistors (with 7-dB gain) driven by a smaller 25-W device. There are a total of 540 modules on the antenna.

Fixed-site variants of this radar are known as the GE-592 and the AN/FPS-117. The latter uses a 24 ft by 24 ft antenna with 44 rows. It is a minimally attended radar whose antenna operates within a radome for use in northern regions. The tactical mobile version of this radar is the TPS-117, which was shown in Fig. 1.8.

Active Aperture, Electronically Steered Phased Array An example of the composition of a T/R module as might be used for an active-aperture phased array antenna is illustrated in Fig. 10.4. The T/R switches select between the transmitter and the receiving paths. The circulator, which might be the largest and heaviest component on the module, performs the function of the duplexer. The receiver protector (which is a diode limiter) provides further protection of the low-noise amplifier (LNA). The same phase shifter is

Figure 10.4 Example of the composition of a T/R module that might be used for an active-aperture phased array radar.



used for both transmitting and receiving. Many other parts of a T/R module are not shown in this illustration, such as the module controller and the power conditioner.[21] The module controller obtains a beamsteering command from a central computer and calculates the correct settings for the phase shifter. To minimize power consumption, the power amplifiers and the LNA might be gated off when the controller is on. The module controller might also perform self-testing and reporting of the status of the module. The power conditioner is important in keeping the efficiency of the module as high as practical.

The Pave Paws electronically steered array radar, also known as the AN/FPS-115, is a UHF radar developed by Raytheon that was the first all solid-state active aperture electronically steered phased array radar. Its function was to detect and warn of sea-launched ballistic missiles fired at the United States. This radar was discussed in Sec. 9.9. It operated from 420 to 450 MHz with a peak power of 600 kW and an average power of 150 kW, which corresponds to a duty cycle of 0.25. Its diameter was 72.5 ft, with room to grow to 102 ft. An individual module delivered 340 W of peak power with 39 percent efficiency.[17,22] The pulse width was 16 ms. There were two phased array faces per site to cover approximately 240° in azimuth. Each antenna face had the capability of operating with 5354 elements, but only 1792 active transceiver modules were used for transmission. Extra elements and a narrow beam were used on receive. (The remaining elements were for future growth.) A transmitting module was made up of seven Class-C silicon bipolar transistors in a 1-2-4 amplifier configuration. It has been said[22] that "system performance is maintained with as many as 200 modules per face inoperative." An enlarged version of the Pave Paws radar replaced the parabolic torus antennas used in the original Ballistic Missile early Warning System (BMEWS). This version had 850-kW peak power with a 0.30 duty cycle.

THAAD Ground Based Radar This is an example of an active-aperture phased array radar with 25,344 elements, a very large number. It was discussed in Sec. 9.9 and its picture shown in Fig. 9.36. With such a large number of elements, the cost of an individual T/R module must be kept small. If, for example, the cost of an individual T/R module were $1000 each, the total cost of just the modules for this radar would be twenty-five million dollars.

Solid-State Devices Used in Radar[17] As has been mentioned, the transistor amplifier has been the device usually used for radars with high-power solid-state transmitters. At the lower microwave frequencies, the silicon bipolar transistor is usually used; and at the higher microwave frequencies, it has been the gallium arsenide (GaAs) FET transistor. At the higher frequencies, the solid-state power device can also be incorporated as part of a microwave monolithic integrated circuit (MMIC).

The silicon bipolar transistor has been used at microwave frequencies below about 3 GHz (S band). According to Olson,[23] a typical internally matched silicon bipolar transistor operating as a class-C amplifier over the frequency range from 2.7 to 2.9 GHz with a pulse width of 50 μs, 10 percent duty cycle and a supply voltage of 40 V, can have a minimum power output greater than 100 W, a minimum gain of 6.5 dB, and a minimum efficiency of 35 percent.

The power output of the silicon bipolar transistor decreases with increasing frequency. At the higher microwave frequencies, the gallium arsenide FET, often in the form of a MESFET (metal semiconductor field-effect transistor) is capable of greater power than the silicon bipolar transistor. Transistors should be operated at a high duty cycle since the peak power output for pulsed operation cannot be significantly increased over that of CW operation. At *X* band, the power output of such devices might be 10 W. Other devices that have been considered for solid-state power sources include[23] GaAs HEMT (high electron mobility transistor); GaAs-based pseudomorphic HEMT, or PHEMT; GaAs heterojunction bipolar transistor (HBT); and devices employing unconventional materials such as silicon carbide and semiconductor diamond for high temperature, high power operation.[24]

At the higher microwave frequencies where compactness in size is desired, the microwave monolithic integrated circuit (MMIC) has been of interest for T/R modules. Active and passive circuit elements are formed on a semi-insulating semiconductor substrate, usually GaAs to create system architectures that are difficult to realize with less integrated technologies. The benefits of MMIC are due in large part to the batch processing of both the active and passive components on the same substrate. Borkowski[17] lists the advantages of MMIC for radar as low cost, increased reliability, increased reproducibility, and small size and weight. The nonrecurring costs of engineering design of MMICs, however, can be high and design might require a relatively long time. Since MMICs are not well suited for tweaking of the circuits once manufactured, the designs must be tolerant to variations in the processing. Olson[23] states that the power available from MMICs is about 10 W in the frequency range from 3 to 10 GHz and then decreases with increasing frequency at a rate of 6 dB per octave.

Advantages of Solid State The solid-state transistor amplifier has been of interest for radar transmitter applications because of the following:[17]

- Individual solid-state devices have long MTBF (mean time between failures).
- Maintenance is relatively easy with the modular construction of solid state. (A defective module is pulled out and replaced by another.)
- Very wide bandwidths can be obtained (up to 50 percent or more).
- No cathode heater is required (no warm-up time and no heater power to reduce the overall transmitter efficiency).

- Solid-state devices operate at much lower voltages (order of tens of volts) than RF power tubes (order of tens of kilovolts).
- No pulse modulator is required. (When operated as a class-C amplifier, the transistor is self-pulsing in that it automatically turns on when the RF drive signal is applied and it automatically turns off when the drive signal is turned off.)
- Solid-state transistor amplifiers have low noise and good stability (important for detection of small targets in the presence of large clutter echoes).

Another attribute often claimed for a solid-state radar is that many individual devices can fail without significant effect on the overall transmitter power (graceful degradation). The power output in dB varies as 20 log r, where r = ratio of the number of operating devices to the total number of devices.[17] This is correct in principle, but in practice there can be catastrophic failure modes for a solid-state transmitter and, eventually, the modules that fail must be replaced, even if they fail "gracefully." Except for its long pulses and high duty cycle the solid-state transistor is well suited for use in an active-aperture phased array where each element contains its own transmitter/receiver module.

When solid-state transmitters were first proposed for radar, it was said they would be lighter in weight and lower in cost than vacuum tube transmitters. It is not obvious that this has occurred. In some cases in the past when a solid-state transmitter replaced a high-power vacuum-tube transmitter in an existing radar, the solid-state transmitter was heavier and cost more.

Systems Implications of Solid-State Devices Pulse radars typically have been characterized in the past by low duty-cycle waveforms with typical values of duty cycle ranging from approximately 0.001 to 0.01. Power vacuum tubes are well suited for low duty cycles. For a given average power their peak power can be increased by a factor of 1000 or more with little penalty other than the practical problem of making the insulators able to stand off the higher voltages. Semiconductor power devices, on the other hand, cannot be efficiently operated at low duty cycles. For a given average power, the peak power might be less than ten times the average power. Thus replacing a vacuum-tube transmitter with a solid-state device usually means the radar must use high duty-cycle waveforms. High duty cycles mean long pulse widths which have the disadvantage of long minimum ranges. When a short minimum range is important, more than one pulse width might have to be transmitted. The long pulses of solid-state transmitters require pulse compression to achieve good range resolution. The technology of pulse compression has been widely used in radar, but it does have some limitations that short-pulse waveforms do not have. Seldom, however, is the cost of pulse compression and the cost of multiple waveforms considered as a solid-state transmitter cost, even though they increase the total cost of the radar system and are not needed with many vacuum-tube transmitters.

There are at least two reasons why the cost of radars with solid-state transmitters is often higher than those with comparable vacuum-tube transmitters.[12] One is that the efficiency of solid-state transmitters is generally less than that of a high-power vacuum-tube transmitter. The other is that the cost of obtaining power is greater when the total power is obtained with more than one power-source unit. An advantage of low-power solid-state devices for computers and low-power transmitters is that they can be made very compact.

A lot can be placed on a small chip. When the solid-state device has to handle high power, however, as it would for a radar transmitter, there can be a problem in dissipating the heat generated by the power sources. Solid-state devices that have to handle high power have to be spread out over a greater extent of circuit board area to avoid exceeding the heat transfer limits. The size and weight of the solid-state amplifier are therefore determined by the power densities that the amplifier can handle rather than by the size of the individual components. Thus the advantages of photolithographic fabrication of high-density low-power solid-state integrated circuits are not available when the power is high. Spreading the solid-state devices over a wide area in order to provide for heat dissipation can result in lower efficiency due to higher power-combining losses in transmission lines and in combiners. Dissipation of the higher heat levels requires heavier heat sinks and results in a heavier transmitter.[12]

It has been known for a long time that the cost of a single high-power vacuum tube varies as the square root of the output average power. Thus, the lowest cost tube transmitter for a given total power output is the transmitter that uses a single high-power tube rather than multiple tubes. Symons[12] indicates that the cost of a transmitter made up of multiple devices, such as is necessary when using high-power solid-state devices, increases almost linearly with the number of devices. At high powers, therefore, it should be expected that the single vacuum-tube transmitter will be of lower cost than a solid-state transmitter made up of many modules generating the same total power.

Individual solid-state devices can have a much longer life and lower failure rate than an individual vacuum-tube power source. The life of a solid-state transmitter, however, is determined not by the life of a single transistor or a single module but by the life of all the modules and the many other components that make up a transmitter. Vacuum-tube transmitters, when well designed and properly operated, have been known to achieve very long lifetimes, mentioned previously in this chapter. Maintenance of a solid-state transmitter should be easier than maintenance of a high-power vacuum tube transmitter, but the life of a properly designed and operated vacuum tube transmitter should be quite long and not be a serious system problem.

Compared to the high-power vacuum tube, the solid-state transmitter has advantages, but it also has some serious limitations. It is not obvious that current solid-state transmitter technology will cause the high power RF vacuum tube to disappear. Solid-state will be used when its particular advantages are more important than its limitations and higher cost. As happens often in engineering, the radar systems engineer has a number of choices when it comes to selecting the type of RF power source to use for a particular radar system application. The solid-state transmitter is just one of many possibilities that have to be considered for any particular application—unless the customer insists otherwise.

MAGNETRON

The magnetron has been the only high-power RF power source used for radar that is a power oscillator rather than a power amplifier. It is a crossed-field device in that its electric field and its magnetic field are perpendicular to one another. The compact size and efficient operation of the magnetron at microwave frequencies allowed radars to be

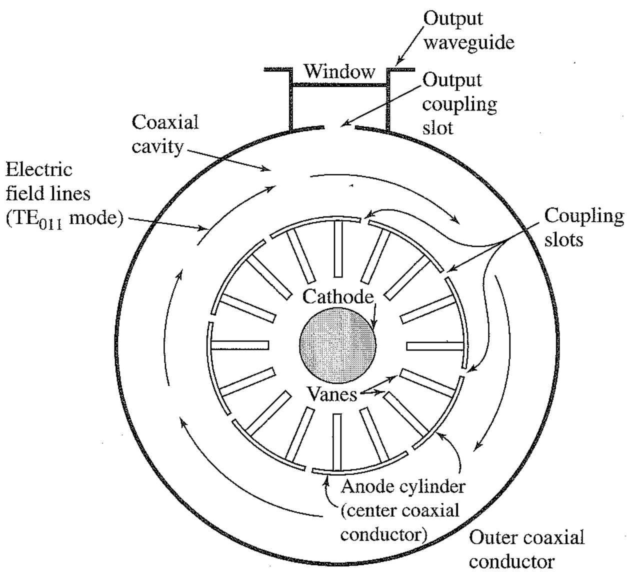
small enough to fly in military aircraft, be mobile for ground warfare, and even be used on submarines.

Coaxial Magnetron A major improvement in the power, efficiency, stability, and life of the original magnetron architecture came about with the coaxial magnetron introduced in the 1960s. The key difference was the incorporation of a built-in stabilizing cavity surrounding the conventional magnetron. Figure 10.5 is a sketch of the cross section of the circular geometry of a coaxial magnetron. At the center is the "fat" oxide-coated cathode. Surrounding the cathode are a number of RF resonant cavities defined by the radial vanes. Between the cathode and the resonant cavities is the interaction space where the electrons interact with the d-c electric field and the static magnetic field in such a manner that the electrons give up their d-c energy to the RF field. The crossed electric and magnetic fields cause the electrons to be "bunched" almost as soon as they are emitted from the cathode. After bunching, the electrons move along in a traveling-wave field that is almost the same speed as that of the electrons.

The frequency of a coaxial magnetron can be changed by mechanically moving one of the end plates, called a tuning piston, of the stabilizing cavity. (The end plate is located in the plane of the paper of Fig. 10.5 and is not shown.) The tuning piston can be positioned mechanically from outside the vacuum by means of a vacuum bellows.

There is also an inverted form of the coaxial magnetron (an inside-out) version with the anode and resonant cavities in the center and the cathode around the outer perimeter of the tube. It is supposed to provide better performance at higher frequencies when the cavity becomes small and the regular type of coaxial magnetron would result in a small cathode.

Figure 10.5 Cross-sectional sketch of a coaxial cavity magnetron.



π Mode It is not easy to describe the theory of operation of a magnetron in a simple manner, so no attempt is made to do so here. A magnetron can oscillate at a number of different, closely spaced frequencies due to various possible configurations of the RF field that can exist between the cathode and the resonant cavities. These different RF field configurations, along with coupling among the many cavity resonators of the magnetron, result in different modes of oscillation. The magnetron can shift, almost unpredictably, from one mode to another (which means from one frequency to another) as the voltage changes or as the input impedance that the magnetron sees changes. The shift from one mode to another (often called *moding*) is especially bad since it can occur when the radar antenna scans and views different environments. It is important to avoid moding.

The preferred magnetron mode of operation is the so-called *π mode* that occurs when the RF field configuration is such that the RF phase alternates 180° (π radians) between adjacent cavities. The advantage of the π mode is that its frequency can be more readily separated from the frequencies of the other possible modes. (An N-cavity magnetron has $N/2$ possible modes of oscillation. The π mode oscillates at only a single frequency, but the other modes can oscillate at two different frequencies, so that the magnetron can oscillate at a total of $N - 1$ different frequencies.)

In the coaxial magnetron, the output of every other resonant cavity is coupled to a stabilizing cavity that surrounds the anode structure, as indicated in Fig. 10.5. The output power is then coupled from the stabilizing cavity. The cavity operates in the TE_{011} mode with the electric lines closed on themselves and concentric with the circular cavity. The RF current at every point on the circumference of the cavity has the same phase, so that the alternate slots which couple to the stabilizing cavity are of the same phase as required for π-mode operation.

Coaxial Magnetron Life The power that can be produced by a magnetron depends on its size. A larger size means more resonators, which then makes it more difficult to separate the various modes of oscillation in a conventional magnetron. The coaxial magnetron, however, with stabilization controlled by the TE_{011} outer cavity permits stable operation with a larger number of resonant cavities, and thus with greater power. The anode and cathode structures of a coaxial magnetron can also be bigger than those of a conventional magnetron, which further allows operation at larger powers. The larger structures permit more conservative design, with the result that the coaxial magnetron exhibits longer life and better reliability than conventional magnetrons, in addition to having a more stable operation. The operating life of a coaxial magnetron tube can be between 5000 and 10,000 hours, which represents a five- to twenty-fold increase compared to conventional magnetrons.[25] It has been said[26] that a VMS-1143 S-band coaxial magnetron operating at 3 MW of peak power in an AN/FPS-6 height-finder radar exceeded a life of 50,000 hours. This tube was likely one-of-a-kind, but it indicates that a magnetron does not necessarily have to have a short life, as once was the case.

Just after World War II and during the 1950s, the life of the early magnetrons was as low as 200 hours mean time between failures, which probably explains why some have had the impression that power vacuum tubes were inherently unreliable and of short life. The demonstrated long lifetimes of the coaxial magnetron and even longer lifetimes of the modern klystron and TWT linear-beam tubes offer ample evidence that the use of

power vacuum tubes need not result in unreliable radars. (The reader might try to recall how often, when watching TV or listening to the radio, the transmission shut down and went off the air because of a failure in the tube transmitter.)

Systems Aspects of the Magnetron The magnetron transmitter was used in a large number of different types of radar transmitters. At one time it was the most popular radar transmitter. Its use, however, has diminished greatly because of the more demanding requirements of modern radars that it cannot readily meet, but which can be satisfied by other RF power sources. Weil[27] describes the problems encountered with the use of the magnetron in his chapter "Transmitters" in the *Radar Handbook.* The major limitations of the magnetron are its limited average power and poor ability to see moving targets in heavy clutter.

Although the magnetron can produce a peak power of several megawatts, its average power is limited to about one or two kilowatts. This may be sufficient for some medium-range radars and for civilian air-traffic control radars that use large antennas, but it is not large enough for many military radar applications. The magnetron is usually smaller in size than many other types of RF power sources, but this is due in part to its low average power.

During World War II, air-surveillance radars did not have an MTI (moving target indication) capability, except for the S-band AN/CPS-1 MEW (Microwave Early Warning) radar which only became available in small numbers near the end of the war. In order for radar to detect aircraft in World War II, targets had to be in the clear outside of the clutter. The bomber aircraft of that time unknowingly cooperated since they were not designed to fly at low altitude below the radar coverage. The early analog MTI radars could use only a single or a double delay-line canceler, so they were limited in MTI improvement factor (or clutter attenuation) to about 20 dB. The magnetron itself limits the improvement factor to perhaps 30 or 40 dB. Therefore, the magnetron was not the limiting factor in early MTI radar performance. This changed when digital signal-processing of MTI signals became available that allowed much better values of MTI improvement factor. Now power amplifiers such as the klystron, TWT, or the transistor have to be used—and not the magnetron—in order to detect small moving targets in heavy clutter, consistent with the full capabilities of digital doppler-signal-processing.

There are several other factors that are not favorable with the magnetron. Its pulse widths are limited from just under 0.1 μs to about 100 μs, but this is usually not a problem. However, modulating the pulse with frequency or phase to achieve pulse compression is quite difficult with a magnetron and has not been done operationally. The signal is not coherent from pulse to pulse so that in MTI radar the phase of the coho (reference oscillator) in the receiver has to be reset every time a new pulse is transmitted. The magnetron frequency drifts with time, which requires that the frequency of the local oscillator in the receiver be continually tuned to the transmitter's frequency (whatever it might be). Magnetrons are noisy and can produce electromagnetic interference at frequencies outside their design frequency range.

Marine Radar Magnetrons The magnetron has proven to be a tube well suited for civil marine radars. These are small devices that generate peak powers between 3 and 75 kW

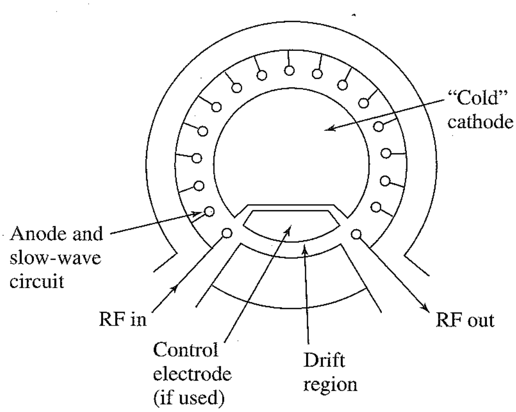
with low average powers of a few watts to a few tens of watts. The marine radar customer demands reliability. When a commercial vessel goes to sea, its captain wants the radar to still be operating when the ship returns to its home port. An example of a magnetron for a civil marine radar is the third generation MG5241 manufactured by EEV of Chelmsford, England. It is an 18-cavity *X*-band magnetron, which produces a peak power of 12.5 kW with an efficiency of 43 percent. The manufacturer claims an expected typical life of over 10,000 h and guarantees a minimum life of 3000 h. Its weight is 625 g (1.4 lb) and it has a volume of 315 cm^3. It operates at a fixed frequency within the band 9.38 to 9.44 GHz.

).5 CROSSED-FIELD AMPLIFIERS

The crossed-field amplifier (CFA) resembles the magnetron in that it employs a magnetic and electric field that are perpendicular to one another.[1,28] It is also similar in appearance to the magnetron, except that the RF circuit is interrupted to provide the input and output connections, Fig. 10.6. CFAs have high efficiency (40 to 60 percent), use lower voltage than linear-beam tubes, and are lighter in weight and smaller in size. They are of wide band (10 to 20 percent), with high peak and average power, and have good phase stability; but their gain is relatively low. They are sometimes used with a high-gain, but lower power, TWT that serves as the driver for the CFA.

CFA Operation There are several different types of crossed-field amplifiers, and they all employ a slow-wave circuit, cathode, and input and output ports. For radar, CFAs usually have the form diagrammed in Fig. 10.6, which is reentrant with distributed emission. Distributed emission means that, like the magnetron, the cathode is adjacent to the full length of the RF structure. Electrons are emitted from the cylindrical cathode, which is coaxial to the RF slow-wave circuit that acts as the anode. The electrons, under the action of the crossed electric and magnetic fields, form into rotating electron (space-charge) bunches, or spokes. These bunches drift along the slow-wave circuit in phase with the RF signal

re 10.6 Simple representation of a sed-field reentrant CFA showing the drift on and the control electrode.



and transfer their d-c energy to the RF wave to produce amplification. The spent electrons that remain after their energy is extracted are collected by the slow-wave anode structure. The electrons that are not collected after their energy is extracted at the output are permitted to reenter the RF interaction area at the input, which is the reason such a tube is called reentrant. Some of the reentering electrons contain modulation (bunched electrons) that will be amplified in the next pass around the RF circuit. To prevent this, a drift space is included between the output and input ports. In the drift space, space charge forces cause the electron bunches to disperse, removing any modulation that accompanies the reentering electrons.

Cold-Cathode Emission In high-power CFAs, the electrons can be generated by cold-cathode field emission rather than thermionic emission with a heated cathode. Cold-cathode emission requires the presence of both the d-c voltage between cathode and anode as well as the RF drive signal applied to the tube. The initiation of electron-emission build-up results from the relatively small number of free electrons present near the cathode surface. Emission is sustained by those electrons not collected by the anode and which are returned to the cathode by the action of the RF field and the crossed electric and magnetic fields. When these electrons strike the cathode they produce secondary electrons that maintain the electron emission process. There is little pulse-to-pulse time jitter in the starting process, and the buildup time is quite rapid ($<$10 ns).[28]

Insertion Loss A CFA has low insertion loss, perhaps less than 0.5 dB. Sometimes this can be an advantage in a multistage transmitter. By omitting the application of d-c voltage to the final stage of a multistage transmitter, the lower level RF drive can be fed directly through the final stage with little attenuation. This allows a radar with such a transmitter to have two power levels, which might be of interest for some system applications.

The low insertion loss of a CFA means that the RF drive power will appear at the output tube with little attenuation. In a low-gain amplifier, such as the CFA, the input power that appears at the output can be a sizable fraction of the total, perhaps one-tenth or more. The *conversion efficiency* of a CFA is defined as

$$\text{Efficiency} = \frac{\text{RF power output} - \text{RF drive power}}{\text{d-c power input}} \tag{10.2}$$

When the RF drive power is included in the output power rather than omitted as it is in Eq. (10.2), it is sometimes called the *power-added efficiency.* That is, power-added efficiency is the total RF power out divided by the d-c power in. Tube engineers like to quote the power-added efficiency instead of Eq. (10.2), since it results in a higher value.

Forward- and Backward-Wave CFAs The interaction of the electron bunches with the RF signal may be with either a forward traveling wave or a backward traveling wave. The type of interaction is determined by the slow-wave circuit. A forward-wave interaction takes place when the phase velocity and the group velocity of the propagating signal along the slow-wave circuit are in the same direction. (The *group velocity* is the velocity with which energy is propagated along the slow-wave circuit, and the *phase velocity* is the velocity of the RF signal on the slow-wave circuit as it appears to the electrons.) To achieve

amplification, the phase velocity must be near the velocity of the electron stream. A backward-wave interaction, as in the CFA device known as the *amplitron,* takes place when the phase velocity and the group velocity are in opposite directions. The forward-wave CFA can operate over a broad range of frequency with a constant anode voltage, and with only a small variation in the output power. On the other hand, the power output of a backward-wave CFA, with a constant anode voltage, varies with frequency. It is like a voltage-tuned amplifier. The power output can vary 100 percent for a 10 percent change in frequency.[29] It is possible, however, with conventional modulator techniques to operate a backward-wave CFA over a wide band with little change in output power. The line-type modulator can be compensated for the power variation with frequency and can hold the variation of output power within acceptable levels. When the anode voltage is properly adjusted, the bandwidth of a backward-wave CFA might be 10 percent. Operation of a forward-wave CFA is more like that of a TWT, and it can obtain bandwidths up to about 20 percent.[28]

High-Gain CFA[1,30] The gain of conventional pulsed crossed-field amplifiers is typically 8 to 15 dB. By designing the cold cathode as a slow-wave circuit, and introducing the RF drive at the cathode emitting surface, it is possible to achieve 15 to 30 dB of gain in a high-power pulse CFA with power, bandwidth, and efficiency comparable to conventional designs. The RF output is taken from the anode slow-wave circuit. This is known as a *high-gain CFA* or a *cathode-driven CFA.* Its higher gain means that less drive power is required. The cathode-driven CFA can also be made to have lower noise than a conventional CFA by 10 to 20 dB if a slightly different configuration is used. It has been said[31] that signal-to-noise ratios greater than 70 dB/MHz were obtained, which are claimed to be comparable to linear beam tubes and 20 to 30 dB better than conventional CFAs. However, both high gain and low noise cannot be obtained simultaneously with the same configuration.

A 1.2-MW peak power *S*-band cathode-driven CFA operating from 3.1 to 3.5 GHz (12 percent bandwidth) achieved 23-dB gain at saturation and 30 dB at reduced peak power, with an efficiency of 53 percent when employing a drive power of 6 kW.[29,32]

Modulating a CFA The CFA can be pulsed-modulated by turning on and off the high voltage between the anode (at ground potential) and the cathode (at a large negative potential). This is called *cathode pulsing.* A forward-wave CFA with cold-cathode electron emission, however, can be pulsed without the need for a high-power modulator as required for cathode pulsing. The d-c operating voltage is applied continuously between cathode and anode. The tube remains inactive until the application of the RF input pulse starts the electron emission process, and amplification then takes place. At the end of the RF drive-pulse the electrons remaining in the tube must be cleared from the interaction area to avoid causing feedback that generates oscillation or noise. In reentrant CFAs, the electron stream can be collected after removal of the RF drive-pulse by mounting an electrode in the cathode, but insulated from it, in the region of the drift space between the RF input and output ports. This is called a *cutoff,* or *control electrode,* and was indicated in Fig. 10.6. A short positive pulse is applied to the cutoff electrode at the termination of the pulse to quench the remaining electron current. This method of modulation is called *d-c*

operation. Weil[1] has said that d-c operation has been seldom used because it requires a large capacitor bank to limit droop of the pulse and because an arc in a d-c operated tube requires a crowbar protective device to quench the arc, which interrupts the operation for a few seconds instead of for only a single pulse.

It is also possible to turn the CFA on and off with just the RF drive pulse, without the need for a positive pulse applied to the cutoff electrode at the end of the drive pulse. The is called *RF keying,* and is a simple method for modulating a CFA. It has not been widely used, however, since there are factors other than modulator size that determine the best method of modulation.[1]

System Implications CFAs in the past have been employed for high-power air-surveillance radars, for power applied at the subarrays of a high-power phased array radar, and as a power booster following a magnetron oscillator. The low gain of CFA, however, requires that there be multiple stages. When used in an amplifier chain, the CFA is generally found in only one or two of the highest power stages. It can be preceded by a medium-power, high-gain traveling-wave tube, a combination that takes advantage of the best qualities of both tube types. The TWT provides high gain and the CFA allows high power to be obtained with high efficiency and lower voltage.

The electrons in the rotating space-charge bunches do not have identical velocities so that random currents are induced in the slow-wave structure, which generates broadband noise. The noise levels in a CFA, therefore, will be higher than those of a linear-beam tube by about 20 to 30 dB.[32]

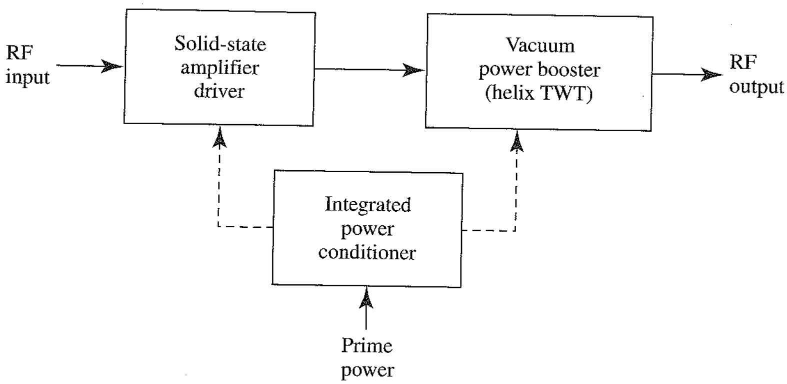
The possibility of pulsing the CFA in a simpler manner than with a cathode pulser has been an attractive feature; but d-c operation and RF keying have limitations that have made cathode-pulsing preferred even though it is heavier. Since high voltage remains on the tube between pulses with d-c operated CFAs, serious levels of noise may be generated even though there is only a small amount of beam current flowing through the tube. With cathode pulsing, on the other hand, high voltage is removed between pulses so that noise is not normally encountered. The increased interpulse noise of the CFA without a cathode pulser, as well as its high level of in-band spurious noise can prevent attaining good MTI performance (large MTI improvement factors) and low time-sidelobes in pulse-compression systems.

The CFA does not seem to generate as much interest as it once did, and it appears to have been overtaken by linear-beam tubes when high performance is required.

10.6 OTHER RF POWER SOURCES

In addition to the RF power sources already mentioned, there have been several other RF devices that been used or proposed for radar application.

Microwave Power Modules (MPM)[33] The microwave power module, outlined in Fig. 10.7, combines in a single unit a solid-state MMIC (monolithic microwave integrated circuit) amplifier driving a moderate-power helix traveling-wave tube, along with an integrated



igure 10.7 Microwave power
odule.

power conditioner in a compact lightweight package. It provides an RF power source with high efficiency, wide instantaneous bandwidth, low noise, and average power levels from several tens to several hundreds of watts. It is smaller and lighter than comparable TWT and solid-state RF power sources and is also capable of operating at high ambient temperatures. The gain of an MPM (nominally 50 dB) is divided between the solid-state driver and the TWT power booster in the ratios from 20/30 to 30/20. The MPM is claimed to be competitive to a TWT or a solid-state power amplifier for radar applications as well as for electronic warfare. It leverages the advantages of both solid-state and vacuum-tube technologies while minimizing their disadvantages.

The MPM seems best suited for the higher microwave frequencies, from S band to K_u band, approximately 2 GHz to 40 GHz. It is expected that an MPM operating over a frequency range from 6 to 18 GHz would produce a peak power of 100 W (up to a 100 percent duty cycle) and be able to be packaged in a space 5/16 in $\times$ 4 in $\times$ 6 in. The MPM is claimed to have an efficiency three times better than that of a comparable solid-state power amplifier and an improvement in noise 30 dB better than a TWT alone. It has been suggested that the MPM can be employed in *C*- and *X*-band phased arrays, synthetic aperture radars for unmanned airborne vehicles (UAV), missile seekers, and airborne turbulence-warning radars.

Although the MPM has been considered mainly for wideband (nonradar) applications operating over one or more octaves, it can also be used for radar with more usual bandwidths. An example is a C-band module described by Smith, Armstrong, and Duthie[34] which can operate over the band from 4 to 6 GHz with an efficiency greater than 35 percent and CW power greater than 125 W. If its operation is restricted to frequencies from 4.6 to 4.9 GHz, the output CW power is 200 W and its efficiency is 50 percent. It is of low weight and small size, producing more than 70 W per pound and 4 W per cubic inch. A limitation for radar application is that it requires a high duty factor (preferably unity or perhaps 50 percent).

Grid-Control Tubes This is the microwave version of the classical triode or tetrode vacuum tube. These tubes employ a cathode to generate electrons, an anode to collect them, and one (if a triode) or two (if a tetrode) control grids in between. A voltage applied to

the control grid acts as a gate, or valve, to control the number of electrons traveling from the cathode to the anode. By varying the voltage on the control grid, the number of electrons that reach the plate also varies. The process by which the electron density of the electron stream is modulated by the signal on the control grid to produce amplification is called density modulation. The grid-controlled tube is capable of high power, wide bandwidth, good efficiency, and inherent long life; but it is of low or moderate gain. It can be used only at the lower radar frequencies.

The performance of density modulated grid-control vacuum tubes is limited by the time it takes for the electrons to transit from the cathode to the anode. The transit time should be small compared to the period of the RF signal to be amplified. For this reason, grid-control tubes have been limited to frequencies below 1 GHz. To minimize transit-time effects, the complete RF input and output circuits and the electrical interaction system are within the vacuum envelope.

Grid-control tubes have been used with success in HF over-the-horizon radar, and in VHF and UHF radars, including the U.S. Navy's E2C airborne early warning radar,[35] and the U.S. Air Force's AN/FPS-85 satellite surveillance radar.[36] Outside of radar, the grid-control vacuum tube has been widely used in commercial VHF and UHF TV transmitters. It is not likely, however, that the grid-control tube will be used much for radar in the future. Solid-state transmitters, even though they may cost more than vacuum tubes, seem to be preferred by those who buy radars at the frequencies where grid-control vacuum tubes have been used previously.

Inductive Output Tube (IOT), or Klystrode[3] This device dates back to work in 1939 by Andrew Haeff,[37] who tried to extend density modulated vacuum tubes to microwave frequencies. Haeff called his device an *Inductive Output Tube* (IOT). He described an IOT that produced 100-W CW power at 450 MHz with 35 percent efficiency and 10-dB gain. This was quite good for its time. Nothing further happened since interest then was mainly on velocity modulated linear-beam tubes.

The IOT was independently reinvented about 30 years later by D. H. Preist and M. B. Shrader under the name *Klystrode.* The name was chosen to signify that the device resembled the klystron in the region between the anode and the collector and it resembled a tetrode in the region between cathode and anode. According to Priest and Shrader,[38] Haeff realized that the conventional triodes and tetrodes were limited by their use of intercepting grids, so in his IOT he replaced the wire grids with an aperture that did not intercept the electrons. A coaxial magnetic field confined the electron stream, as in a klystron or TWT. The action of the grid was to density modulate the electrons, as in a conventional triode, to form bunches of electrons. RF energy was removed from the bunched electron beam by passing it through a resonant cavity that extracted the kinetic energy of the high-velocity electrons. The spent electrons were not collected by the resonators, but by a separate collector. The IOT was like the klystron, except that the density modulation of the electron beam was performed by a grid rather than by an input resonant cavity and drift space that induced velocity modulation on the electrons as in the klystron.

The Klystrode was developed mainly for UHF TV. It can produce many tens of kilowatts average power at high efficiencies (50 to 60 percent) with power gains of 18 to

25 dB. Although it has not been used in radar, it has the potential to provide better performance for UHF radars than the tetrodes used previously.

Constant-Efficiency Amplifier (CEA) One reason for mentioning the IOT and the Klystrode in the above is that they can be modified to produce an amplifier whose efficiency is approximately independent of the power output. Such a device would be of interest for radar when it is desired to shape the radar pulses in order to reduce the time sidelobes of pulse-compression waveforms or to reduce the out-of-band interference generated by a rectangular waveform. Conventional radar RF power sources, such as discussed in this chapter, cannot operate with shaped pulses without a loss in efficiency. A so-called *Constant Efficiency Amplifier* (CEA), however, can be obtained by combining the Inductive Output Tube (IOT) with a multistage depressed collector similar to that used in klystrons and TWTs.[12] The CEA was developed for the television industry. It is claimed that with a CEA the prime power requirements of a TV transmitter can be reduced to one-half compared to a conventional tube transmitter[39] and to one third the prime power of a silicon-carbide solid-state transmitter.[40] The CEA, however, does not operate at frequencies higher than UHF.

Gyrotrons[41–43] The power available from the microwave-radar power sources discussed thus far in this chapter decreases as the frequency is increased. This is due to the resonant structures of the devices becoming smaller with increasing frequency (decreasing wavelength) and the difficulty in removing heat dissipated in small structures. Consequently the power output of a particular type of generator varies approximately inversely as the square of the frequency. The *gyrotron,* on the other hand, does not have this type of frequency dependence since it does not employ a resonant slow-wave structure. Instead, it is based on a fast-wave structure such as a smooth circular tube (one where the phase velocity of the electromagnetic wave is greater than the speed of light). The diameter of the gyrotron circuit can be several wavelengths and the electron beam need not be placed close to the RF structure. Since the size limitations of conventional microwave power sources with resonant circuits are not present in gyrotrons, their power handling capability can be considerably greater. The gyrotron is of interest as a potential source of high peak and average power at millimeter wavelengths. It has also been considered for operation at microwave frequencies, but it has not been able to compete with more conventional microwave power sources.

The gyrotron, also known as a *cyclotron resonance maser,* employs a strong externally applied axial magnetic field to cause electrons within the circular fast-wave structure to rotate at the electron cyclotron frequency, which is $\omega_c = eB_0/m\gamma$, where e = electron charge, m = electron rest mass, B_0 = axial magnetic field, γ is the relativistic factor which is $[1 + (e/mc^2)V_0]$, c = velocity of light, and V_0 = beam voltage. The beam voltage and the corresponding electron velocity are high enough to cause relativistic effects. The electrons follow helical paths around the lines of the magnetic field in the presence of an electromagnetic wave with a transverse component of electric field. The electrons become phase-bunched in their cyclotron orbits as a result of the relativistic mass change of the electrons. Electrons that lose energy to the electromagnetic wave become lighter and accumulate phase lead and catch up with the electrons that gain energy and become heavier and accumulate phase lag.

The frequency of the gyrotron is determined by the magnetic field and not by the characteristic size of the interaction region as it is in microwave power tubes. The magnetic field must be quite large in order to generate cyclotron oscillations at the higher frequencies. For this reason, the magnets used for millimeter wavelength gyrotrons are usually superconducting, which can be a burden for some applications, especially if the device has to be operated in a cryostat at liquid helium temperatures. However, the development of magnets based on high-temperature superconducting materials and efficient closed-cycle refrigerators, or cryocoolers, offers the possibility of using supercooled gyrotrons in mobile platforms such as ships and aircraft.

Since the diameter of the gyrotron RF circuit is normally large compared to the wavelength of the electromagnetic wave it generates, it is possible to have a higher order mode or multiple modes of the electromagnetic field. Operation in more than one mode can result in operation at more than one frequency. The design of a gyrotron requires that care be given to insure stable, single-frequency operation in only one mode.

The gyrotron oscillator at 94 GHz can produce CW power greater than 100 kW and peak pulse power of 1 MW, with efficiencies of about 30 percent. A quasi-optical gyrotron was tunable from 80 to 130 GHz (a half octave) by varying the magnetic field.[44] The power was relatively constant over this frequency range, averaging about 60 kW.

The gyrotron can be operated as an amplifier as well as an oscillator. Generally, more power can be obtained from a gryrotron oscillator than the gyrotron amplifier, but the amplifier might have some advantages in radar when doppler processing is important—just as at microwave frequencies. The electron beam of a *gyroklystron* passes through two or more resonant cavities with standing-wave fields separated by drift spaces. A *gyroTWT* is one which operates with traveling wave fields, similar to a microwave TWT. The gyroklystron has a smaller relative bandwidth than the gyroTWT, but it is capable of higher gain, efficiency, and output power. A *gyrotwystron* operates similarly to a microwave twystron in that it uses standing-wave fields to bunch the electrons and a traveling-wave field to extract the energy. The relative bandwidths of millimeter-wave gyrotron amplifiers are generally less than the relative bandwidths that can be obtained with microwave power amplifiers.

The specifications for a particular experimental gyroklystron designed for radar operation at a center frequency of 94 GHz required that it have an average power of 10 kW, peak power of 80 kW, efficiency of 20 percent, and bandwidth of 600 MHz.[45]

Multiple-Beam Klystrons[46] In a conventional klystron with a single electron beam, the power can be increased by increasing the already high beam voltage. Instead of increasing the beam voltage to obtain greater power, it is possible to employ many electron beams that pass through individual channels located in a single multichannel drift tube. The total power is the sum of the power extracted from each of the lower-current electron beams. The number of beams has been from 6 to 61. Such a power generator is known as a *multiple-beam klystron* (MBK).

The significant reduction in beam voltage results in reduced size and weight compared to a conventional klystron of comparable power. Its magnet and power supply are smaller and lighter. The geometry of the multiple beams of the MBK allows an increase in bandwidth because of an increase in perveance. The lower voltage also can eliminate the need for lead shielding to screen against X-ray radiation.

The high-power multiple-beam klystron was first seriously examined in the U.S. in the 1950s, but interest was not sustained because the needs for high power were satisfied by other more conventional types of klystrons. Tube engineers in the Soviet Union began seriously investigating the MBK in the 1970s, and were successful in producing RF power sources that have been widely used in Russian radar systems. An example of an MBK produced and marketed by the Russian Company ISTOK is their IKS-9007, a six-cavity, 36-beam klystron. It operates at 3.3 GHz with a 200-MHz bandwidth (6 percent), peak power from 500 to 800 kW, duty cycle of 0.02, gain of 40 dB, and an efficiency of 40 to 50 percent. The beam voltage is 28 to 32 kW. The klystron tube weight is 25 kg and the solenoid magnet weight is 95 kg, which is said to be 2 to 3 times less than single-beam klystrons of similar performance.

ISTOK has also applied the multiple-beam technology to the traveling wave tube and the inductive output tube.

).7 OTHER ASPECTS OF RADAR TRANSMITTERS

Pulse Modulators[47,48] The function of the modulator is to turn the transmitter on and off to generate the desired waveform. When the waveform is a pulse, the modulator is sometimes called a *pulser.* Each RF power source has its own particular characteristics that determine the type of modulator to be used. The magnetron modulator, for instance, has to handle the full pulse power. The transistor amplifier, on the other hand, requires no modulator at all since the transistor is turned on and off by the presence or absence of the input pulse. The full power of the klystron and the traveling-wave tube can be switched by a modulator handling only a small fraction of the total electron-beam power if the tubes are designed with a modulating anode or a shadow grid. The crossed-field amplifier (CFA) is often cathode-pulsed, requiring a full-power modulator. Some CFAs, however, can be d-c operated, which means they can be turned on by the start of the RF input pulse and turned off by a short, low-energy pulse applied to a cut-off electrode. Similar to the transistor amplifier, some lower power CFAs require no modulator since they can be turned on and off by the start and stop of the input RF pulse.

The basic elements of one type of radar modulator is shown in Fig. 10.8. Energy from an external power source is accumulated in the energy-storage element at a slow rate during the interpulse time. The charging impedance limits the rate at which energy is delivered to the storage element. When the pulse is ready to be formed, the switch is closed and the stored energy is quickly discharged through the load to form the d-c pulse that is applied to the RF power device. During the discharge part of the cycle, the charging impedance prevents energy from the storage element from being returned to the energy source.

Line-Type Modulator In this device a delay line, or pulse forming network (PFN), is used as the storage element. The switch can be a hydrogen thyratron, mercury ignitron, a silicon controlled rectifier (SCR), saturable reactor, or other device that can initiate the discharge of the PFN to form a rectangular pulse. The shape and duration of the pulse are

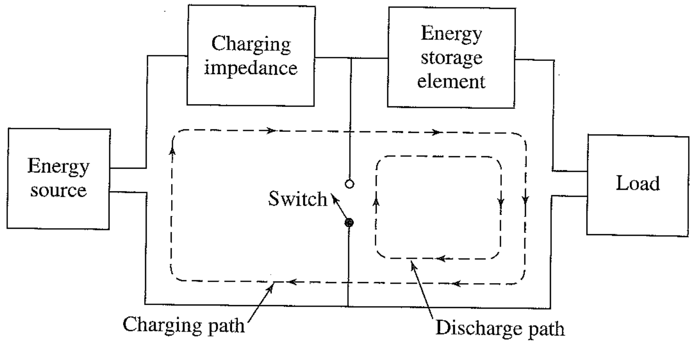


Figure 10.8 Basic elements of one type of radar pulse modulator.

determined by the passive elements of the PFN. The switch has no control over the pulse shape other than to initiate it. The pulse ends when the PFN has discharged sufficiently to allow the switch to close and recover its voltage hold-off capability. The trailing edge of the pulse is usually not sharp since it depends on the discharge characteristics of the PFN. The line-type modulator is simple, compact in size, and can tolerate abnormal load conditions. It has been widely used in the past for magnetron pulsing.

Active-Switch Modulator The switching element in this type of modulator has to be able to be turned off as well as on. Originally the switch was a vacuum tube and the modulator was called a hard-tube modulator to distinguish it from the gas-tube switch often used in a line-type modulator. In addition to the vacuum tube, the switch can be a semiconductor device such as a silicon controlled rectifier.

There are three types of active-switch modulators: (1) cathode pulsers that control the full beam power of the RF tube, (2) mod-anode pulsers that are required to switch at the full beam voltage of the RF tube but with little current, and (3) grid pulsers that operate at a far smaller voltage than that of the beam.

Unlike the line-type modulator, the switch in the active-switch modulator controls both the beginning and the end of the pulse. The energy storage element is a capacitor. To prevent droop in the pulse shape due to the exponential nature of a capacitor discharge, only a small fraction of the stored energy is extracted from the capacitor for the pulse to be delivered to the tube. In high-power transmitters with long pulses the capacitance must be very large. A large capacitance might be obtained with a collection of capacitors known as a *capacitor bank.*

The active-switch modulator permits more flexibility and precision than the line-type modulator. It can provide excellent pulse shape, varying pulse durations and prfs, including mixed pulse lengths and bursts of pulses with close spacings. It is, however, of greater complexity and weight than a line-type modulator.

Crowbar Protective Device Power tubes can develop internal arc discharges with little warning. When an arc occurs in an unprotected device, the capacitor bank discharges large currents through the arc and the tube can be damaged. The tube can be protected with a device called an *electronic crowbar,* which places a short circuit across the capacitor bank

to transfer its stored energy. When a sudden surge of current due to a fault in a protected power tube is sensed, the crowbar switch is activated within a few microseconds. The current surge also causes the circuit breaker to open and deenergize the primary source of power. The name "crowbar" is derived from the analogous action of placing a heavy conductor, like a crowbar, directly across the capacitor bank. A crowbar is required for a high-power active-switch modulator because of the large amount of energy that is stored in its capacitor bank. Crowbars are not usually needed with line-type modulators which store less energy in their pulse-forming network. Line-type modulators are designed to discharge safely all the stored energy each time a pulse is generated.

Transmitter Noise and Spectrum[49] An RF power source can produce spurious, unwanted outputs as harmonics of the fundamental frequency, adjacent-band (out-of-band) noise, and in-band noise. Harmonics and adjacent-band noise can be reduced 30 to 60 dB by using high-power filters. Shaping of the pulse to make it more rounded and less rectangular reduces out-of-band signal energy. In-band spurious signals and noise cannot be readily filtered since these unwanted signals are within the frequency range of the desired signal spectrum. The in-band noise is greater in some RF power sources than in others. For example, Weil states[49] that the noise level in a 1-MHz bandwidth of a conventional CFA is typically 50 to 60 dB down, but is down 90 dB or better in linear-beam tubes.

Section 3.7 discussed the effects of equipment instabilities on the amount of clutter cancellation, or improvement factor, that can be achieved in MTI radars. The typical noise level in conventional CFAs can set a limit on the achievable MIT improvement factor to perhaps the vicinity of 45 dB or so. Linear beam tubes, on the other hand, are capable of very high MTI improvement factors except for limitations introduced by their modulators and power supplies. The ripple on the modulator voltage and the variation of the high-voltage power supply (HVPS) must be sufficiently small to obtain the large improvement factors needed in high-performance radars.

In a staggered prf MTI system (Sec. 3.3) the variation of the interpulse period causes a variation in the HVPS voltage, which can be a significant source of transmitter instability. The consequent reduction in improvement factor that would result needs to be corrected, as indicated by Weil.[49]

The transmitter and its modulator can also distort pulse compression waveforms and introduce spurious time-sidelobes. Active-switch modulators are more likely to allow low pulse-compression time-sidelobe levels as compared with the time sidelobes produced by line-type modulators.

REFERENCES

1. Weil, T. A. "Transmitters." In *Radar Handbook,* 2nd ed. M. Skolnik (Ed.). New York: McGraw-Hill, 1990, Chap 4.
2. Gilmour, A. S., Jr. *Microwave Tubes.* Norwood, MA: Artech House, 1986, Chap. 16.
3. Granatstein, V. L., R. K. Parker, and C. M. Armstrong. "Vacuum Electronics at the Dawn of the Twenty-First Century." *Proc. IEEE* 87 (May 1999), pp. 702–718.

4. News article from *Microwaves & RF,* (November 1984), p. 31.
5. Smith, M. J., and G. Phillips. *Power Klystrons Today.* New York: John Wiley, 1995, Sec. 7.2.3.
6. Staprans, A. "Linear Beam Tubes." In *Radar Technology,* E. Brookner (Ed.). Boston: Artech House, 1977, Chap. 22.
7. Gilmour, A. S., Jr. Ref. 2, Chap. 4.
8. Phillips, R. M., and D. W. Sprehn. "High-Power Kystrons for the Next Linear Collider." *Proc. IEEE* 87 (May 1999), pp. 738–751.
9. Staprans, A., E. W. McCune, and J. A. Ruetz. "High-Power Linear-Beam Tubes." *Proc. IEEE* 61 (March 1973), pp. 299–330.
10. Dodds, W. J., T. Moreno, and W. J. McBride, Jr. "Methods for Increasing the Bandwidth of High Power Microwave Amplifiers." *IRE WESCON Conv. Rec.* 1, pt. 3 (1957), pp. 101–110.
11. Gilmour, A. S., Jr. Principles of Traveling Wave Tubes. Boston: Artech House, 1994, Sec. 18.4.
12. Symons. R. S. "Tubes: Still Vital After All These Years." *IEEE Spectrum* 35 (April 1998), pp. 52–63.
13. Gilmour, A. S., Jr. Ref. 11, Chap. 13.
14. Gilmour, A. S., Jr. Ref. 2, Chap. 11.
15. Luebke, W. and G. Caryotakis. "Development of a One Megawatt CW Klystron." *Microwave J.* 9, no. 8 (August 1966), pp. 43–47.
16. Symons, R. S., and J. R. M. Vaughan. "The Linear Theory of the Clustered-Cavity™ Klystron." *IEEE Trans.* PS-22 (October 1994), pp. 713–718.
17. Borkowski, M. T. "Solid-State Transmitters." *Radar Handbook,* 2nd ed., M. Skolnik (Ed.). New York: McGraw-Hill, 1990, Chap. 5.
18. Lee, K., C. Corson, and G. Mols. "A 250 kW Solid State AN/SPS-40 Radar Transmitter." *Microwave J.* 26 (July 1983), pp. 93–105.
19. Dyck, J. D., and H. R. Ward. "RAMP's New Primary Surveillance Radar." *Microwave J.* 27 (December 1984), pp. 105–113.
20. Merrill, P. R. "A 20 kW Solid-State L-Band Transmitter for the RAMP PSR Radar." *Microwave J.* 31 (March 1988), pp. 165–173.
21. Chilton, R. H. "MMIC T/R Modules and Applications." *Microwave J.* 30 (September 1987), pp. 131–146.
22. Hoft, D. J. "Solid State Transmit/Receive Module for the Pave Paws Phased Array Radar." *Microwave J.* 21 (October 1978), pp. 33–35.
23. Olson, F. A. "Microwave Solid-State Power Amplifier Performance: Present and Future." *Microwave J.* 38 (February 1995), pp. 24–46.
24. Trew, R. J., J-B Yan, and P. M. Mock. "The Potential of Diamond and SiC Electronic Devices for Microwave and Millimeter-Wave Power Applications." *Proc. IEEE* 79 (May 1991), pp. 598–620.

25. Butler, N. "The Microwave Tube Reliability Problem." *Microwave J.* 16 (March 1973), pp. 41–42.
26. Advertisement of the Electron Device Group, Varian Beverly Division, Beverly, MA. (Varian is now known as CPI, Inc.)
27. Weil, T. A. Ref. 1, Sec. 4.2.
28. Gilmour, A. S., Jr. Ref. 2, Sec. 13.3.
29. Weil, T. A. "Comparison of CFA's for Pulsed-Radar Transmitters." *Microwave J.* 16 (June 1973), pp. 51–54, 72.
30. Kaisel, S. F. "Microwave Tube Technology Review." *Microwave J.* 20 (July 1977), pp. 23–42.
31. Anonymous. "Cathode-Driven Crossed-Field Amplifer." *Microwave J.* 31 (February 1988), pp. 208–209.
32. Sivan, L. *Microwave Tube Transmitters.* London: Chapman & Hall, 1994, Sec. 7.4.
33. Abrams, R. H., Jr. "The Microwave Power Module: A 'Supercomponent' for Radar Transmitters." *Record of the 1994 IEEE National Radar Conf.,* Atlanta, GA, pp. 1–6, IEEE No. 94CH3359–7.
34. Smith, C. R., C. M. Armstrong, and J. Duthie. "The Microwave Power Module: A Versatile RF Building Block for High-Power Transmitters." *Proc. IEEE* 87 (May 1999), pp. 717–737.
35. Yingst, T. E., et al. "High-Power Gridded Tubes—1972." *Proc. IEEE* 61 (March 1973), pp. 357–381.
36. Reed, J. E. "The AN/FPS-85 Radar System." *Proc. IEEE* 57 (March 1969), pp. 324–335.
37. Haeff, A. V. "An Ultra-High-Frequency Power Amplifier of Novel Design." *Electronics* 10 (February 1939), pp. 30–32.
38. Preist, D. H., and M. B. Shrader. "The Klystrode—An Unusual Transmitting Tube with Potential for UHF-TV." *Proc. IEEE* 70 (November 1982), pp. 1318–1325.
39. Symons, R. S. "The Constant Efficiency Amplifier." *NAB Broadcast Engr. Conf. Proc.* (1997), pp. 523–530.
40. Symons, R. S., et al. "The Constant Efficiency Amplifier—A Progress Report." *NAB Broadcast Engr. Conf. Proc.,* 1998.
41. Granatstein, V. L., and I. Alexoff. *High-Power Microwave Sources.* Boston: Artech House, 1987.
42. Gilmour, A. S., Jr. Ref. 2, Chap. 14.
43. Felch, K. L., et al. "Characteristics and Applications of Fast-Wave Gyrodevices." *Proc. IEEE* 87 (May 1999), pp. 752–781.
44. Manheimer, W. M. "On the Possibility of High Power Gyrotrons for Super Range Resolution Radar and Atmospheric Sensing." *Int. J. Electronics* 72, nos. 5 and 6 (1992), pp. 1165–1189.

45. Blank, M., B. G. Danly, and B. Levush. "Circuit Design of a Wideband W-Band Gyroklystron Amplifier for Radar Applications." *IEEE Trans.* PS-26 (June 1998), pp. 426–432.

46. Gelvich, E. A., et al. "The New Generation of High-Power Multiple-Beam Klystrons." *IEEE Trans.* MTT-41 (January 1993), pp. 15–19. See also the ISTOK Web Site at www.istok.com.

47. Weil, T. A. Ref. 1, Sec. 4.8.

48. Ewell, G. W. *Radar Transmitters.* New York: McGraw-Hill, 1981.

49. Weil, T. A. Ref. 1, Secs. 4.6 and 4.7.

PROBLEMS

10.1 One way to define the efficiency of a transmitter is RF power out, P_{out}, divided by the prime power in, P_{in}. (a) Plot the power dissipated, $P_{dis} = P_{in} - P_{out}$, as a function of the transmitter efficiency, ϵ, for a fixed power out. [Make the ordinate the ratio (power dissipated)/(power out).] (b) If the output power has to be 30 kW, what power will be dissipated with a transmitter having a 15 percent efficiency? (c) If the transmitter efficiency can be increased to 50 percent, what is the amount of power to be dissipated? (d) What disadvantages occur with low efficiency?

10.2 (a) In a solid-state transmitter (a solid-state "bottle") with 300 modules, what would be the reduction in output power if 20 modules were to fail? (b) What fractional reduction in radar range would this cause?

10.3 (a) If 10 percent of the modules in an active-aperture phased array radar fail, what would be the reduction in transmitter power? (b) What would be the reduction in the maximum radiation power density? (c) What would be the reduction in radar range?

10.4 For an air-traffic control radar application, compare the advantages and disadvantages of a solid-state transmitter, klystron transmitter, and magnetron transmitter.

10.5 (a) If one wanted a radar transmitter with a 10 percent bandwidth, what options are available to the radar system designer and which RF power source appears the most desirable? (You may have to make some assumptions about the application.) (b) If one wanted a radar transmitter with 40 percent bandwidth, what options are available and which of these options might you choose? (Include the reason for your choice.) (c) Are there any undesirable consequences with your choice for (b) that you might have to live with?

10.6 What are the advantages and disadvantages of the gyroklystron (amplifier) for radar application at 94 GHz (millimeter waves)?

10.7 How can a tube designer achieve a large bandwidth with a klystron type of power tube?

10.8 When might the systems engineer choose to use a traveling wave tube over a klystron for a high-power radar application?

10.9 For a high-power UHF radar transmitter application, compare the advantages and disadvantages of solid state, the grid-control vacuum tube, the constant-efficiency amplifier, and the klystron.

10.10 When might a magnetron be desirable for use in radar applications?

10.11 What factors might be involved when a radar systems engineer tries to choose among the crossed-field amplifier, TWT, and Twystron for some radar application?

10.12 If the R&D genie were to grant a radar systems engineer many wishes, what improvements might the radar systems engineer want to have for a radar transmitter?